Conducting Fog Research and Abatement Using Unmanned Aircraft Systems (UAS)

Michael Willette

University of North Dakota

Thesis Defense

28 November 2023

Committee: Dr. David Delene, Dr. Aaron Kennedy, Dr. Marwa Majdi

What is Fog?

- An assortment of small hydrometeors suspended at the Earth’s surface that reduces horizontal visibility…

- **Mist**: between 7 statute miles (11.2 kilometers) and 5/8 statute miles (1 kilometer)

- **Fog**: below 5/8 statute miles (1 kilometer)

Photo courtesy of David Delene: 20230508 1116 UTC

Multi-car wreck near Jamestown. Photo courtesy of N.D. Highway Patrol and the Jamestown Sun.

Why Fog?

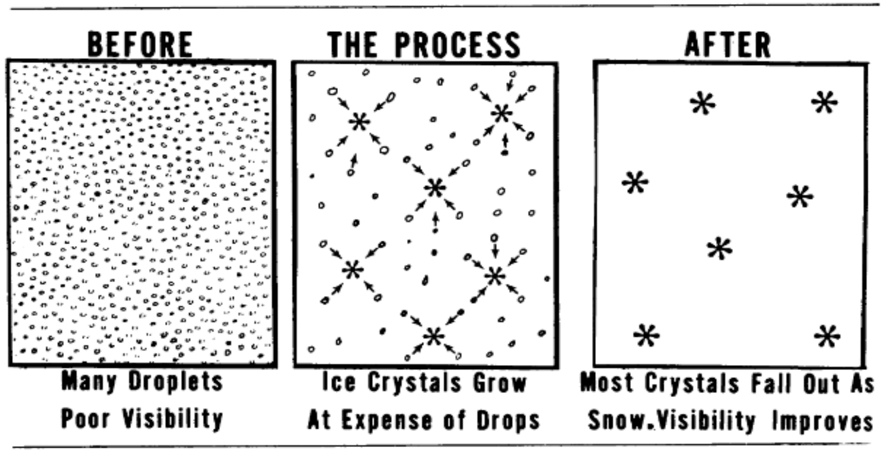
- 38,700 vehicle crashes annually, with 16,300 injuries and over 600 fatalities. (U.S. Department of Transportation 2022)
- Transportational (land, sea, air) economic losses are similar to those of severe weather. (Gultepe et al. 2007)
- Visibility reductions responsible for majority of weather-related aviation accidents. (Gultepe et al. 2007, 2017)
- Of fatal weather-related aviation accidents, fog and low ceilings are the most prevalent factors. (Capobianco and Lee 2001)

Fog Dispersal (Abatement)

-40 °C | -20 °C | 0 °C

Ice Fog	Ice and Supercooled Fog	Supercooled Fog	Warm Fog
Stable	Metastable	Metastable	Stable

- Dispersal largely preventative.
- Conventional aircraft downwash has limited effectiveness.
- Success is limited to transportation of anthropogenic vapor sources.



Supercooled Fog Dissipation Process

Credit: Lease and Zeigler (1972)

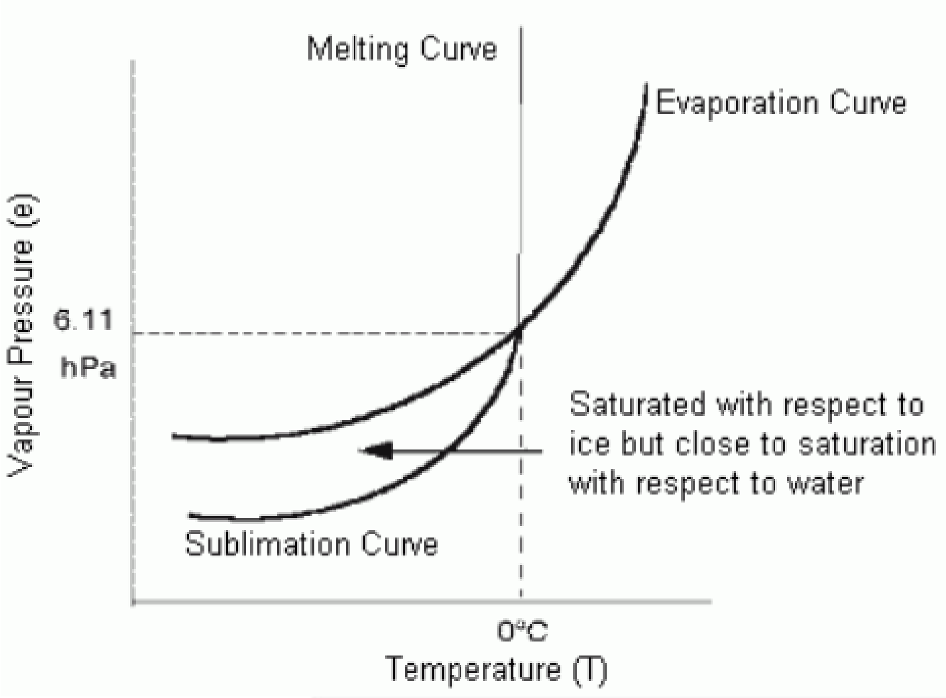
Least common, most accomplished dispersal operationally.

- Most common in the mid-latitudes.
- Two main processes:
  - Physical removal
    - Sound waves
    - Sprays
    - Airmass removal
  - Evaporation
    - Heat
    - Hygroscopic materials

Supercooled Fog Dispersal

Supercooled Fog Formation → Ice crystal growth potential via Wegener-Bergeron-Findeison process → Heterogeneous Nucleation / Homogeneous Nucleation → Gravity-induced Fallout → Increasing visibilities, dispersal

Heterogeneous nucleation through silver iodide



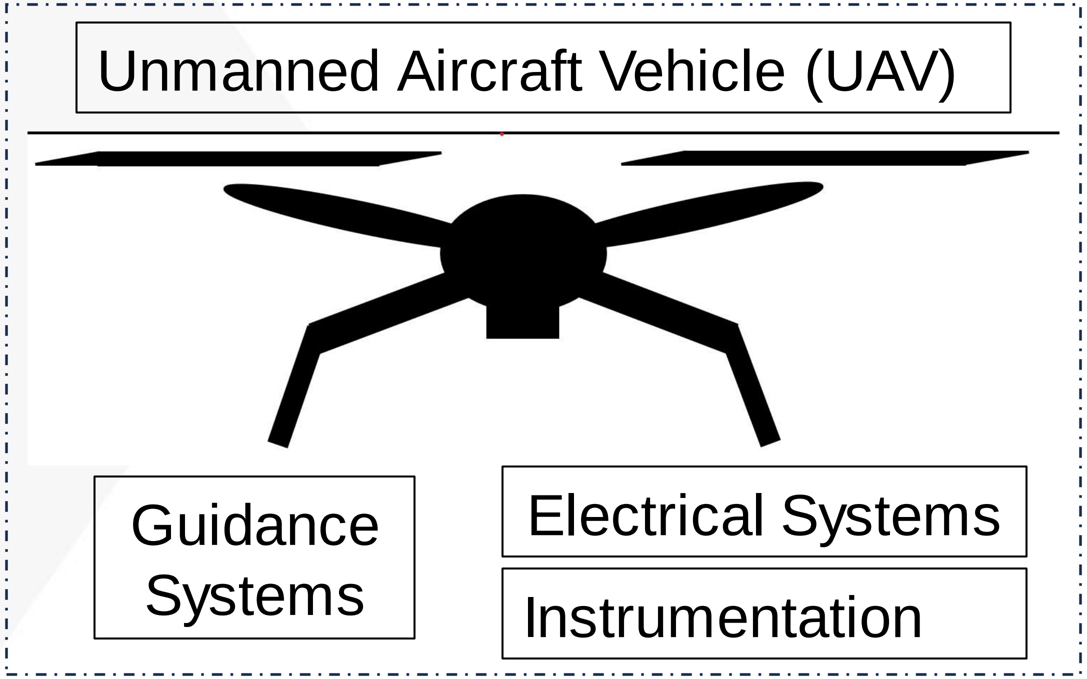
Source: weather.gov.

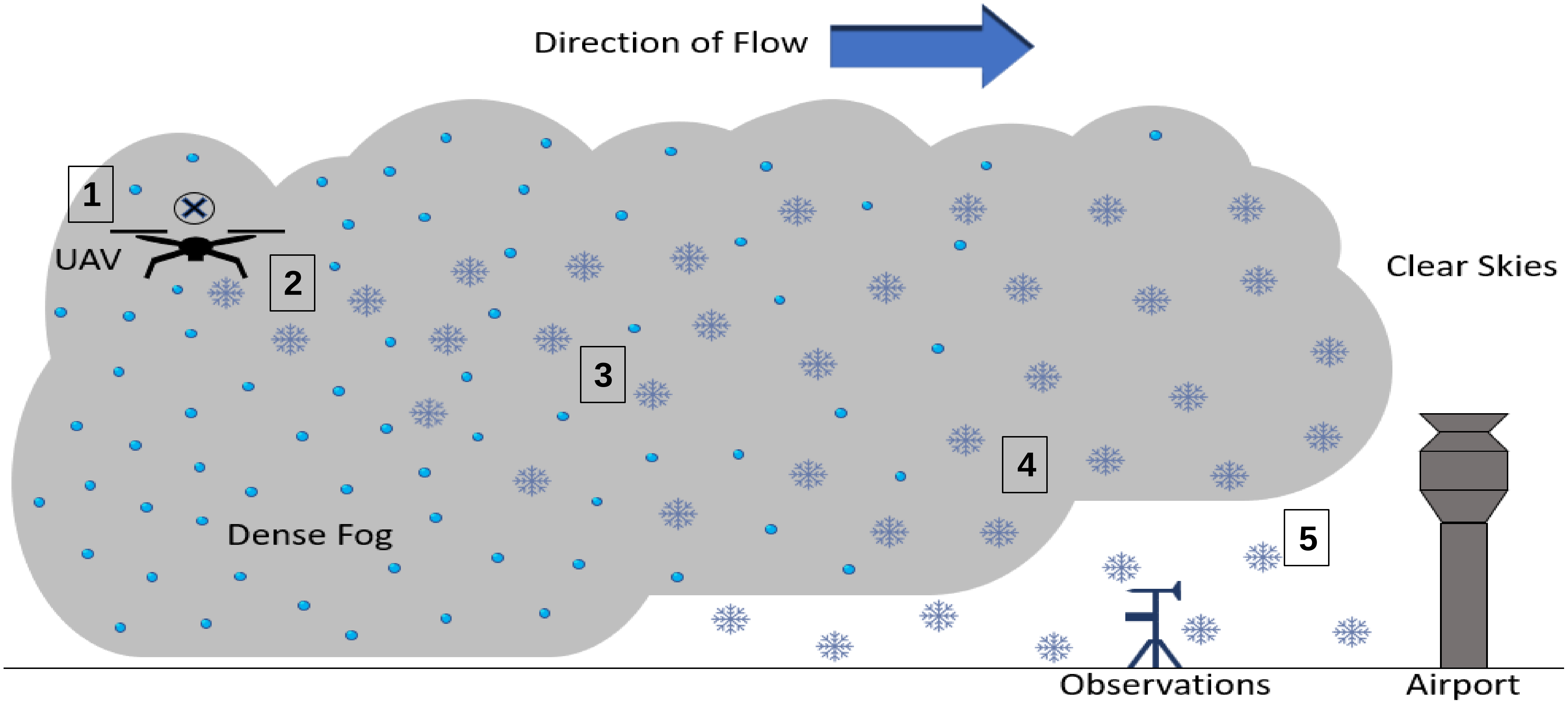
Source: Bulletin of the American Meteorological Society 1965, Volume 46, Issue 6

An Emerging Platform

- Existing dispersal methods have used conventional aircraft.
- Near-surface restrictions constrain conventional aircraft.
- Unmanned Aircraft Systems (UAS) is a promising platform for operation within the boundary layer.

Unmanned Aircraft System (UAS) Platform





1. UAV flies upwind of airport runway, just below top of fog layer.
2. UAV releases seeding material, instigating ice crystal growth.
3. Ice crystals grow at expense of droplets.
4. Ice crystals fall through the extent of cloud.
5. Cloud bases rise, dispersal commences.

Objectives

Two main objectives: Determine the…

Research: efficacy of the UAS platform to acquire in-situ microphysical data
Abatement: feasibility of a supercooled fog dispersal project in the Red River Valley

Supplemental objectives include…

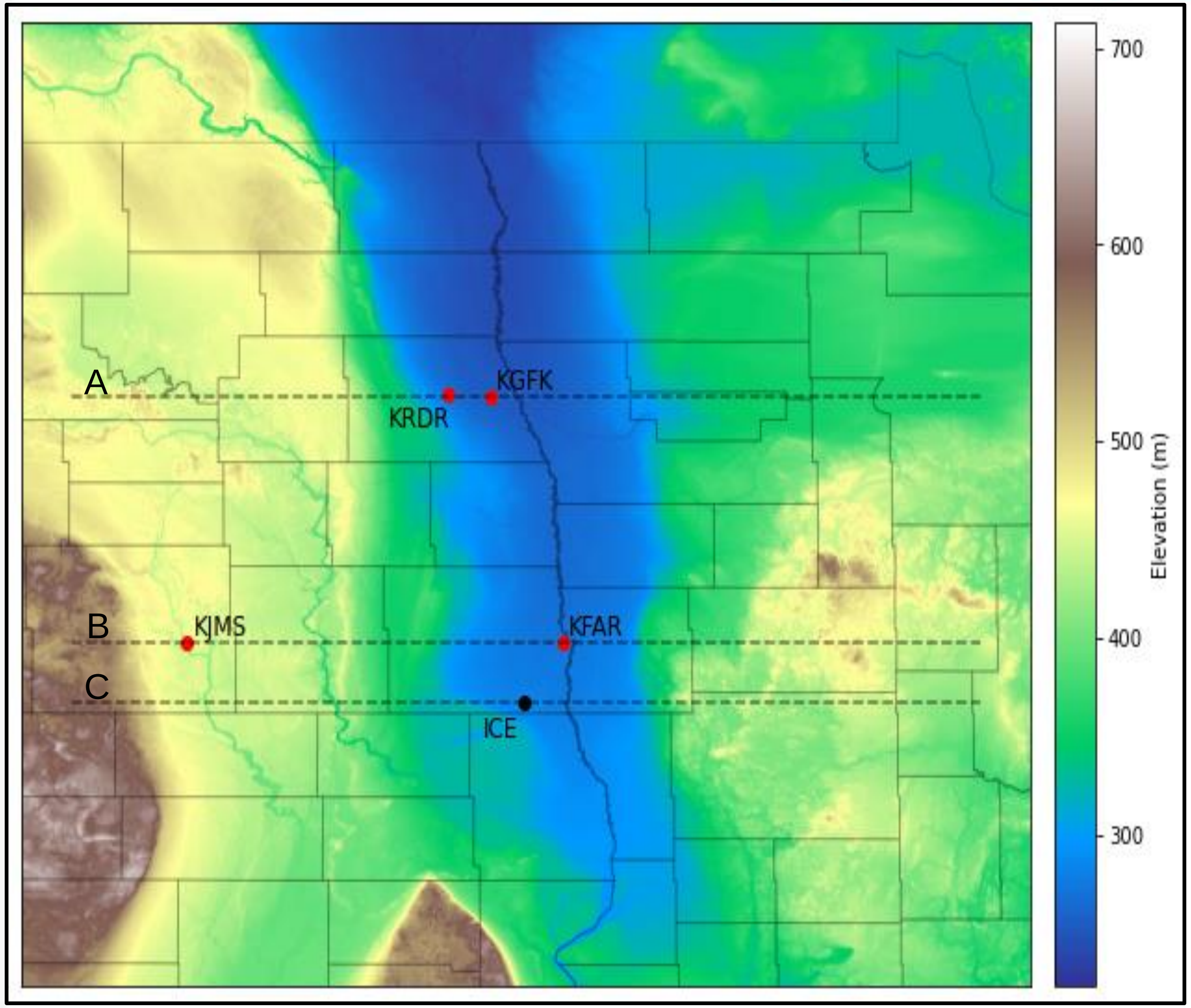
- Procure a fog climatology and determine an operational period.
- Obtain FAA approval for UAS platform implementation.
- Procure an UAV capable of missions within adverse conditions.
- Employ and examine relevant miniaturized instrumentation.
- Perform UAS platform test flights.

Methodology

Fog Climatology: The Red River Valley

- Valley formed from glacial effects (Brooks 2017)
  - Flat smooth low-elevation terrain
  - Rock/sediment deposition along edges

- Intracontinental, high-latitude placement allows for seasonal snowpack buildup



Fog Climatology: ASOS Stations

Three Red River Valley stations:

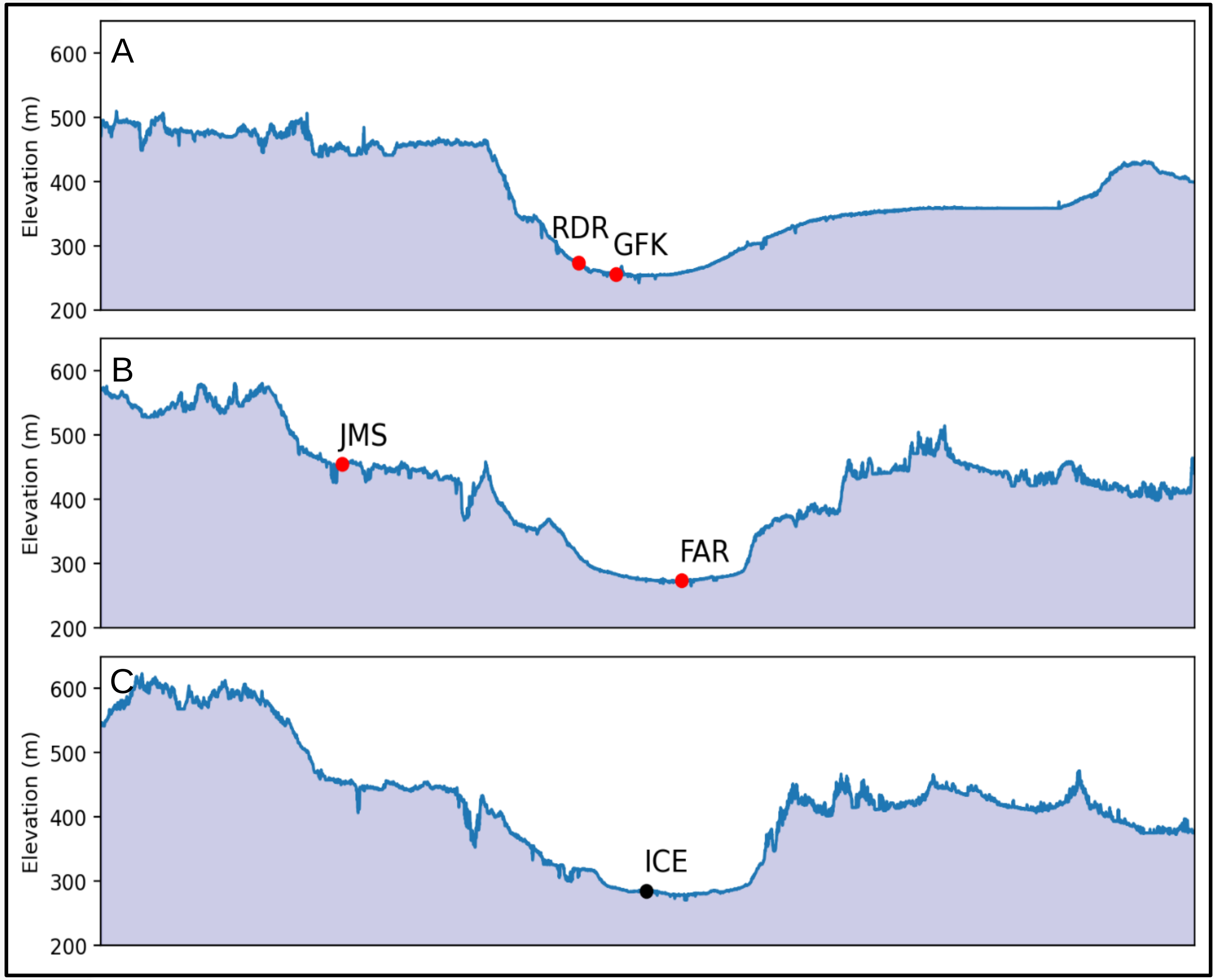
- KGFK: Grand Forks International Airport
- KFAR: Hector International Airport
- KRDR: Grand Forks Air Force Base

One additional North Dakota Station:

- KJMS: Jamestown Regional Airport

Mission Headquarters (no ASOS):

- ICE: Ice Crystal Engineering Headquarters

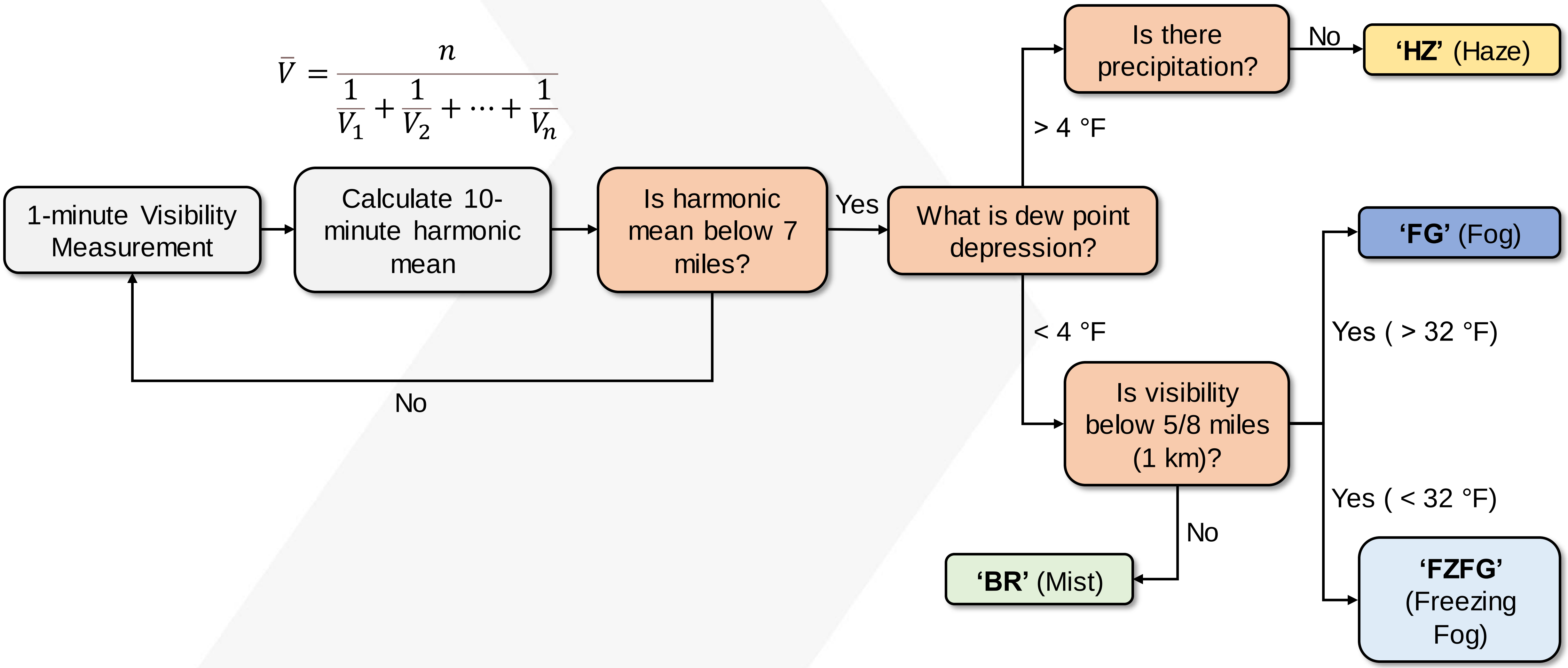


Fog Climatology: The Process

- 30-year sampling period: 1989-2019
- Occurrences of fog (‘FG’) and/or mist (‘BR’) in present weather are grouped by hour for each calendar day.
- Concurrent hydrometeor or non-hydrometeor occurrences are excluded (i.e. rain, snow, drizzle, etc).
- Only the first occurrence during each hourly period is included.
- Wind (< 10 m/s) and temperature (< 0 °C) thresholds are applied.

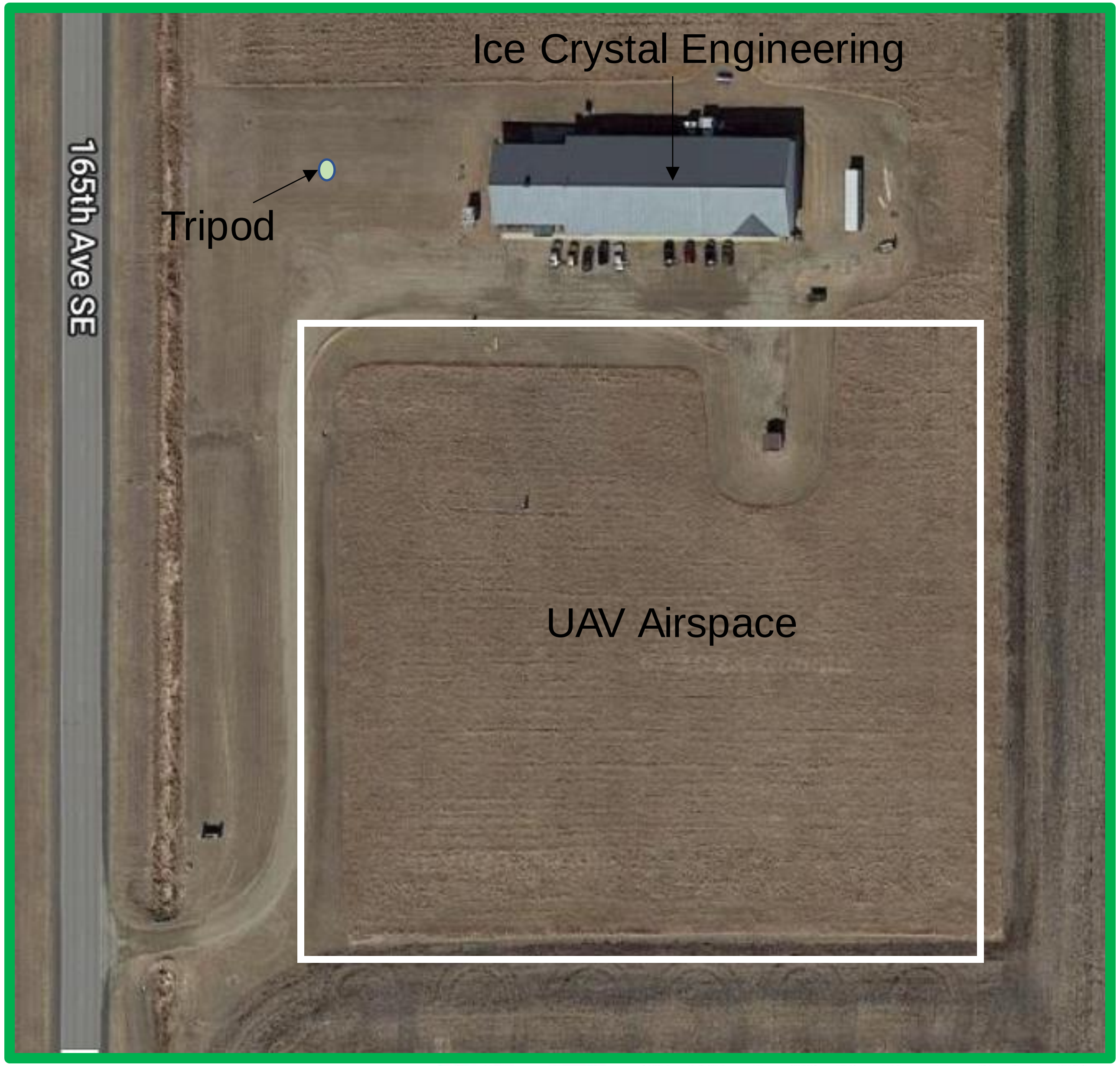
Fog Climatology: ASOS Obscuration Algorithm

$$\bar{V} = \frac{n}{\frac{1}{V_1} + \frac{1}{V_2} + \cdots + \frac{1}{V_n}}$$



UAS Platform Airspace

- FAA Waver (2 years).
- Located 21 miles SW of Hector International Airport (KFAR).
- Located within the eastern Red River Valley at Ice Crystal Engineering (ICE) headquarters.



Credit: Alex Sailsbury and Michael Willette

Unmanned Aircraft Vehicle (UAV)

Diameter	1620 mm
Maximum Takeoff Weight	25 kg
Maximum Takeoff Payload	6 kg
Flight Time Estimates	32.5 min (4 kg Payload) 28.9 min (6 kg Payload)
Battery Capacity	4 x 30,000 mAh
Autopilot	Pixhawk Cube
Radio Control (RC) Controller	2.4 GHz, 8 km range
Datalink	900 MHz, Botlink XRD LTE
Lighting	6x Firehouse ARC XL Strobes
Landing Gear	Fixed and Removable
Arms	Removable
Propellers	29" Lightweight Carbon Fiber

UNIVERSITY OF NORTH DAKOTA

Instrumentation: IMet-XQ2

- Second-generation radiosonde quality instrument (InterMet Systems)
- Parameters:
  - Temperature
  - Relative Humidity
  - Pressure
  - Location (GPS)
- Proper aspiration is vital for temperature, relative humidity sensors.

Credit: InterMet Systems, intermetsystems.com

Measurement	Sensor	Range		Accuracy	Resolution	Response
Temperature	Bead Thermistor	-90 °C	50 °C	± 0.3 °C	0.01 °C	1.0 s
Humidity	Capacitive	0.0 %	100 %	± 5 %	0.1 %	0.6 - 10.9 s
Pressure	Piezoresistive	10 hPa	1200 hPa	± 1.5 hPa	0.01 hPa	0.01 s
GPS	Ublox CAM-M8	0.0 m	50,000 m	12 m (vert.)	2.5 m	1.0 s

Instrumentation: MiniOFS

- Low-cost miniaturized instrument by Sten Löfving (Optical Sensors, Inc.).
- Optical receiver is sensitive to backscattered light around 25 cm.
- Sensitive to direct solar radiation; easy oversaturation.
- Visibility measurements up to 4000 m (can be more).

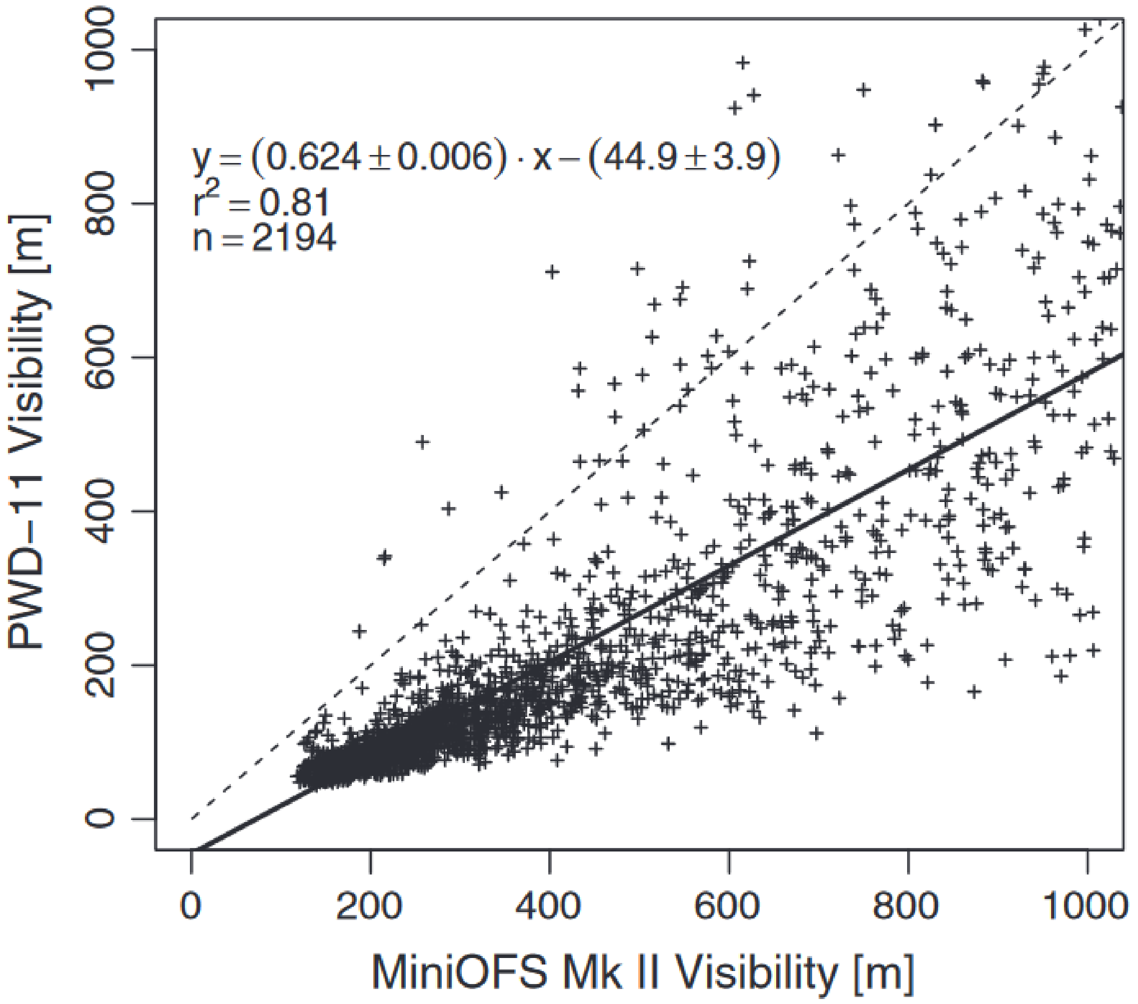
Analog Output	Analog 0-5 Volt
Digital Output	RS 232
Update Time	30 s
Warmup Time	60 s
Operational Temperature Range	-20 °C to +50 °C
Visibility Range	20 m to 4000 m
Wavelength	850 nm
Optical Output Power (IR LED)	~ 3 mW
Housing	Anodized Aluminum

Credit: Optical Sensors Inc.

Instrumentation: MiniOFS

- Comparison to a Vaisala PWD-11 visibility showed successful identification of dense fog. However…(Michna et al. 2013)
  - MiniOFS tends to overestimate visibilities below 1000 m.
  - Considerable light reflection and oversaturation occurs
- 70% collection efficiency for balloon-borne cloud water sampler (500m threshold) (Zinke et al. 2013)
- Successfully distinguished dew events from fog events (1000m threshold) (Riedl et al. 2022)

Takeaways: Good for fog detection. Concerns with overestimation and oversaturation.



Credit: Michna et al. 2013

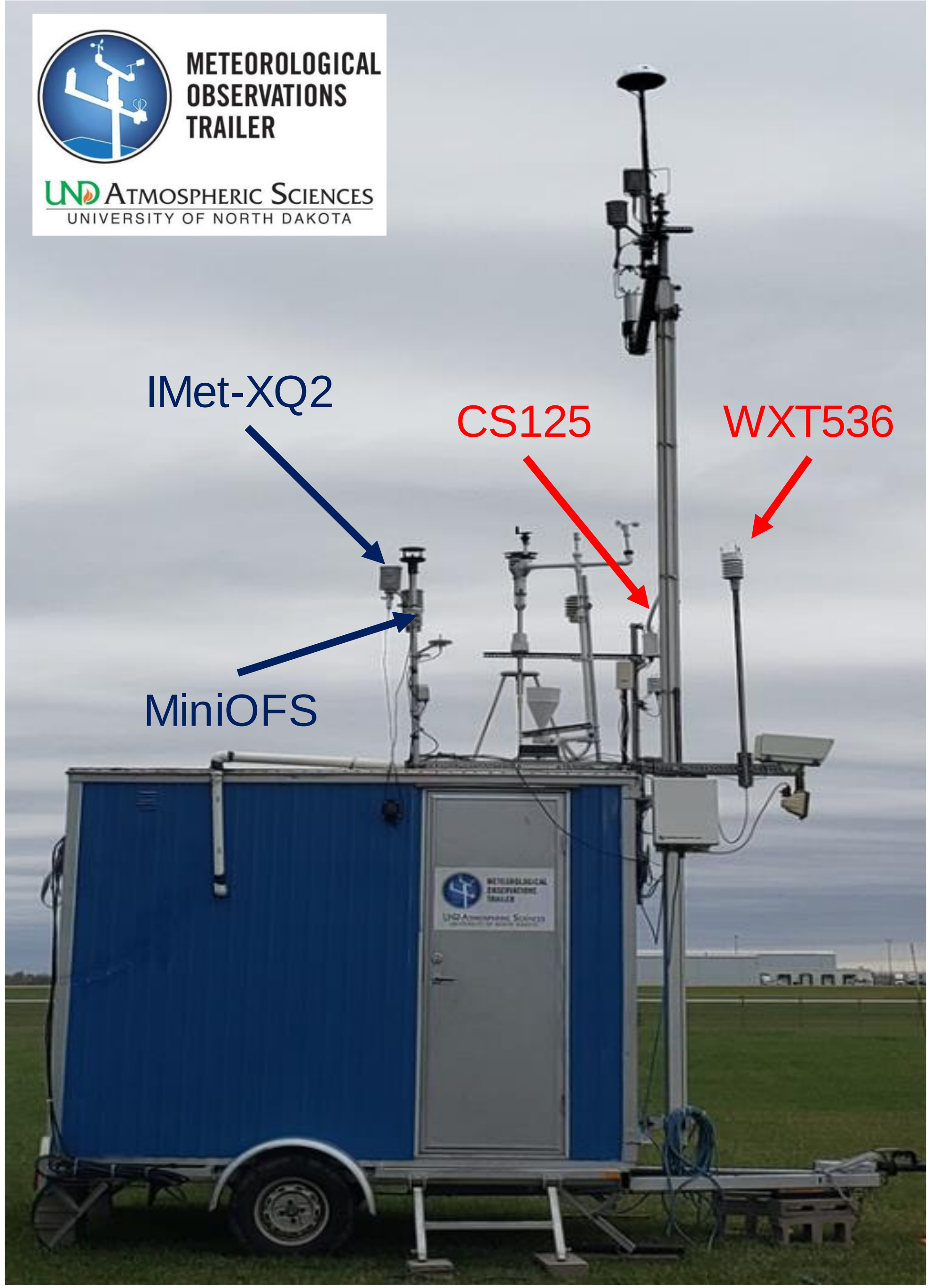
Instrumentation Analysis

With newly developed miniaturized sensors, it is important to compare to industry-standard instruments.

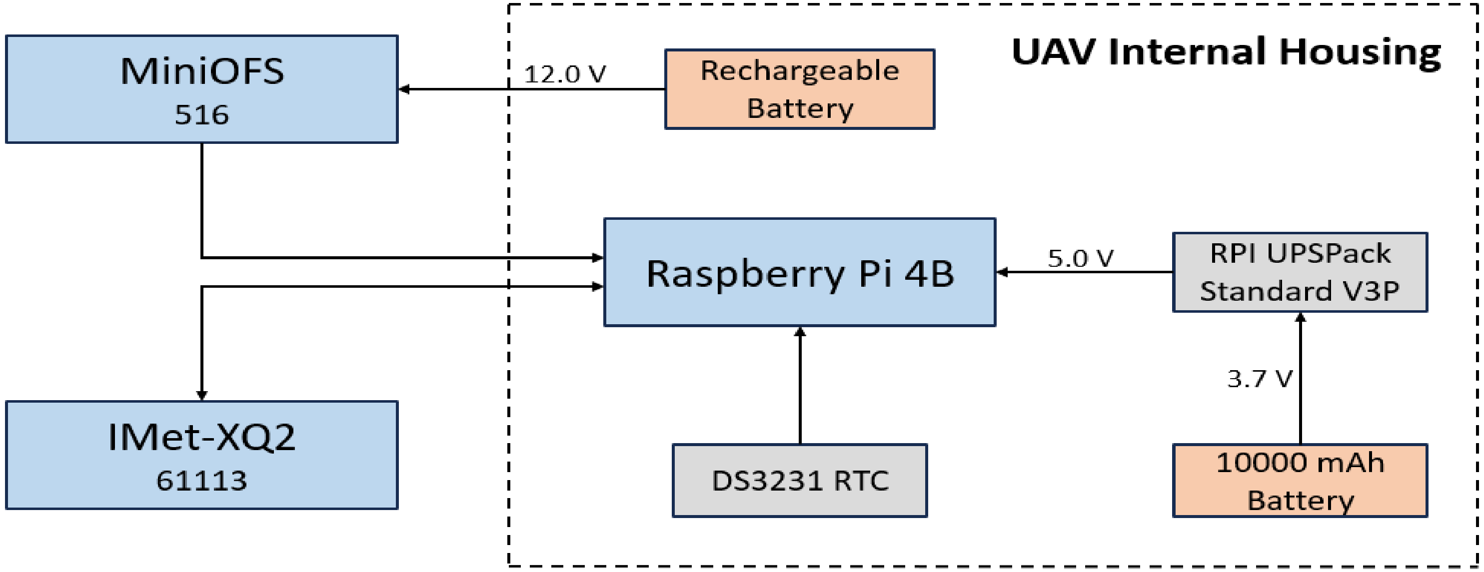
Sampling Period: September 1st, 2021 to December 9th, 2021

Response (Dependent) vs. Predictor (Independent)

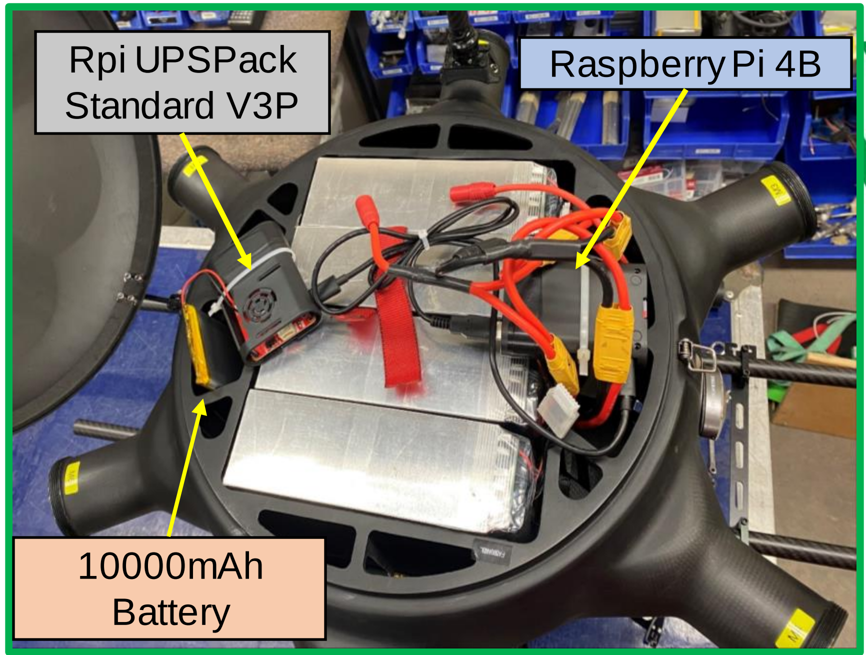
	Temperature	Relative Humidity	Visibility
IMetXQ2	Yes	Yes	No
MiniOFS	No	No	Yes (Backwards Scattering)
WXT536	Yes	Yes	No
CS125	Yes	Yes	Yes (Forward Scattering)

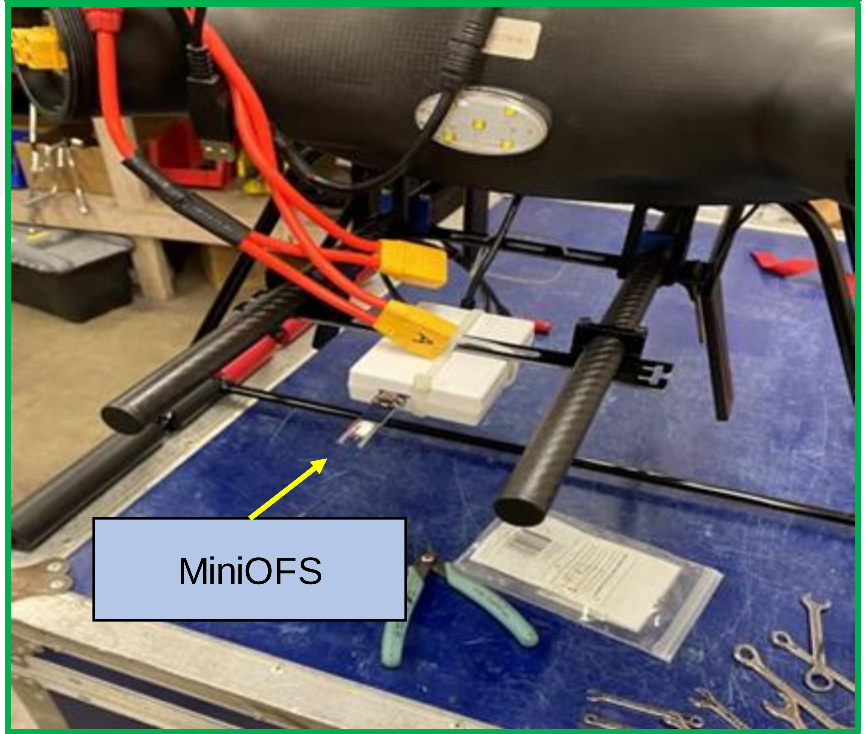


Airborne Platform: UAS



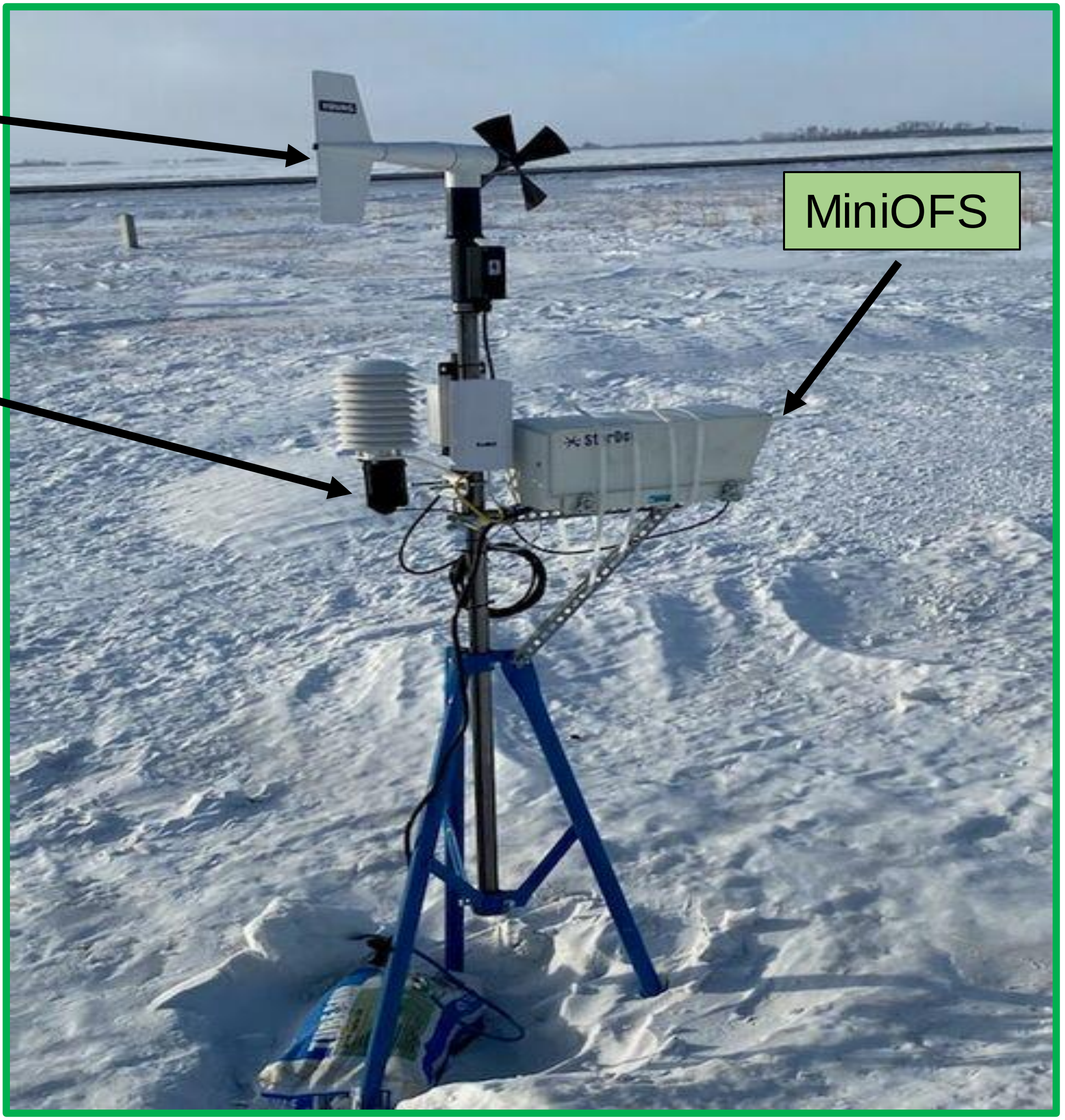
- **<u>Instrumentation</u>**: IMet-XQ2, MiniOFS
- **<u>Raspberry Pi 4B</u>**: Records and stores instrument data
- **<u>DS3231</u>**: Real-time clock module
- **<u>10000 mAh Battery</u>**: Power source for Raspberry Pi 4B
- **<u>Rpi UPSPack Standard V3P</u>**: Converts 3.7V power from battery to 5V for Raspberry Pi 4B
- **<u>Rechargeable Battery</u>**: Power source for MiniOFS

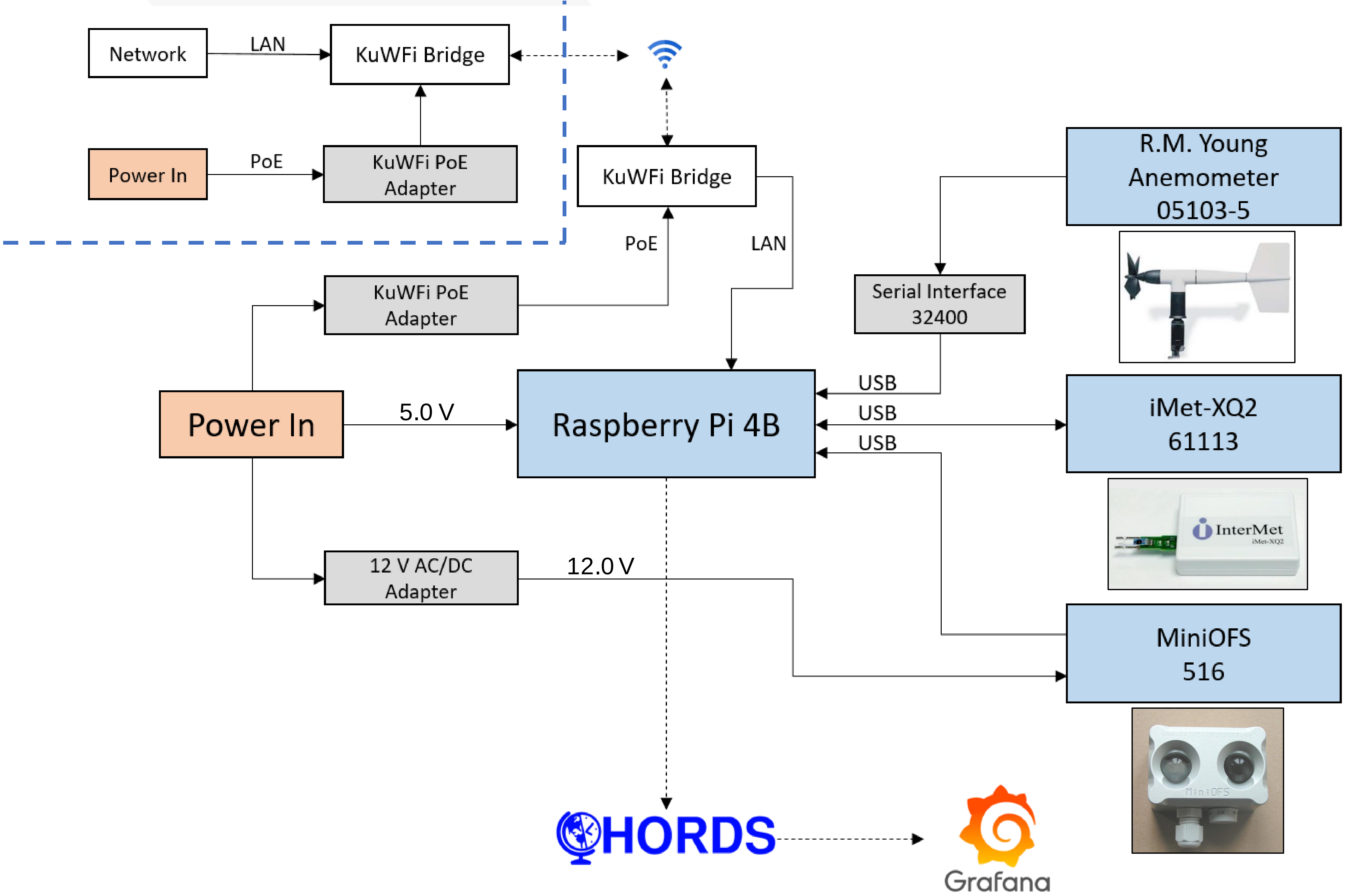




Ground Platform: Tripod

- ***Young Anemometer***
  - Wind Speed
  - Wind Direction
- ***IMet XQ2 UAV Sensor***
  - Pressure
  - Temperature
  - Humidity
- ***MiniOFS Optical Sensor***
  - Visibility
  - Solar Irradiance
  - Extinction Coefficient

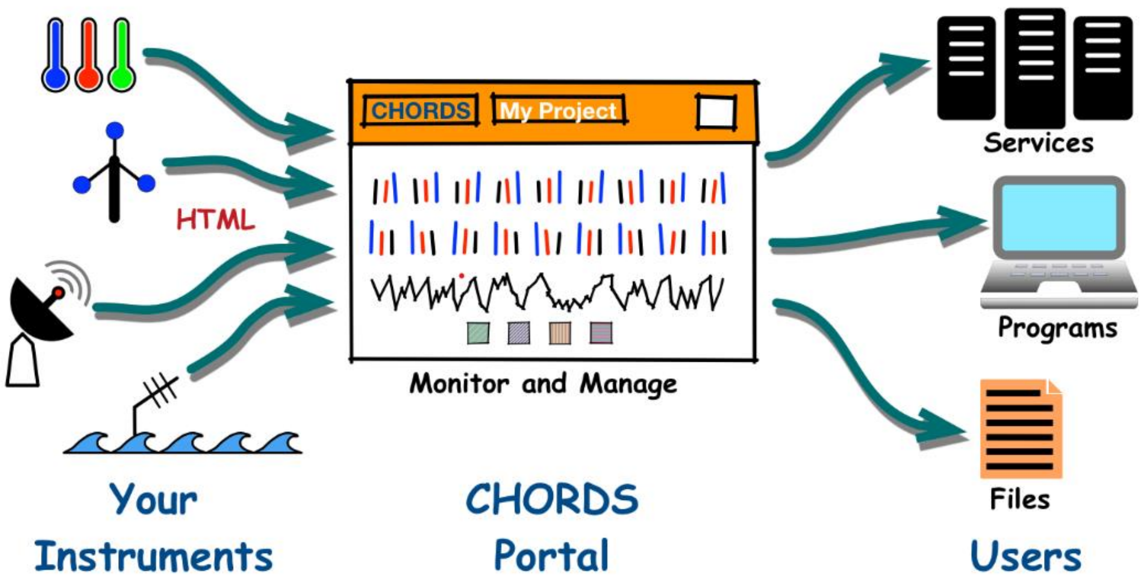




Network
LAN
KuWFi Bridge
Power In
PoE
KuWFi PoE Adapter
KuWFi Bridge
PoE
LAN
R.M. Young Anemometer 05103-5
Serial Interface 32400
KuWFi PoE Adapter
Power In
5.0 V
Raspberry Pi 4B
USB
USB
USB
iMet-XQ2 61113
InterMet
12 V AC/DC Adapter
12.0 V
MiniOFS 516
CHORDS
Grafana

Data Acquisition

- All instrument data is recorded and stored on a Raspberry Pi 4B on both platforms.
- Python-based instrument acquisition scripts available through the Airborne Data Processing And Analysis (ADPAA) software package. (Delene 2011)
- For tripod:
  - Data pushed to CHORDS server
  - Data visualized through Grafana
- For UAV: Data recorded by Pixhawk Cube is accessible through the ArduPilot MissionPlanner program.



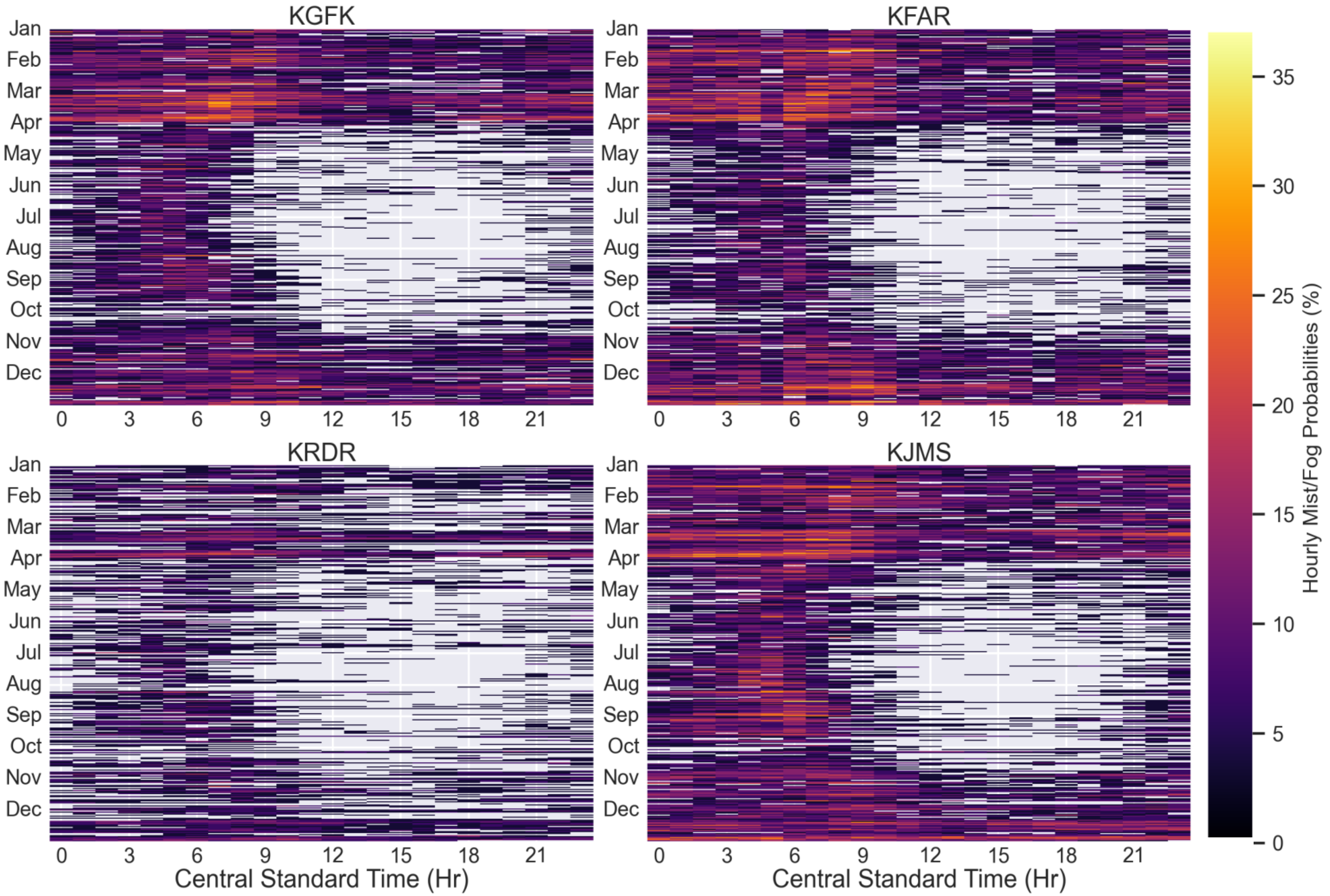
Source: CHORDS, https://earthcubeprojects-chords.github.io/

Instrument	Baudrate	Data Bits	Parity	Stop Bit	Sampling Rate
IMet-XQ2	57,600 bits/s	8	No	1	1 s
MiniOFS	1,200 bits/s	8	No	1	30 s
Young	9,600 bits/s	8	No	1	1 s

Grafana

Results and Discussion

Low Visibility (Mist/Fog) Climatology



All heatmaps use a probability of occurrence:

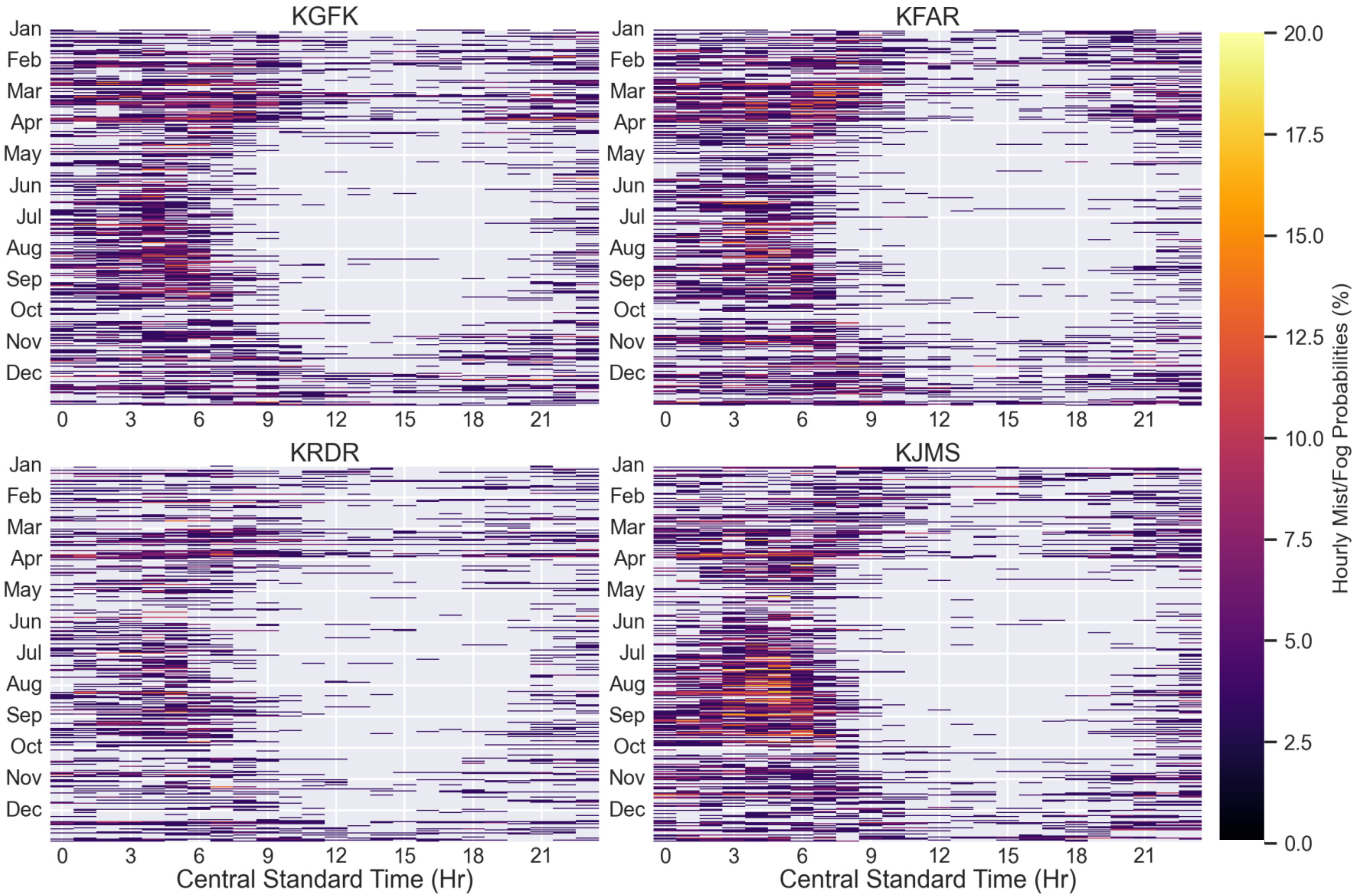
$$P_h = \left(\frac{n_h}{N}\right) \times 100,$$

where,

- n_h is number of occurrences during hourly period
- N is the total possible outcomes (30)
- P_h is the probability of occurrence

Takeaways: Similar patterns for mist/fog at each station, diurnal and seasonal trends

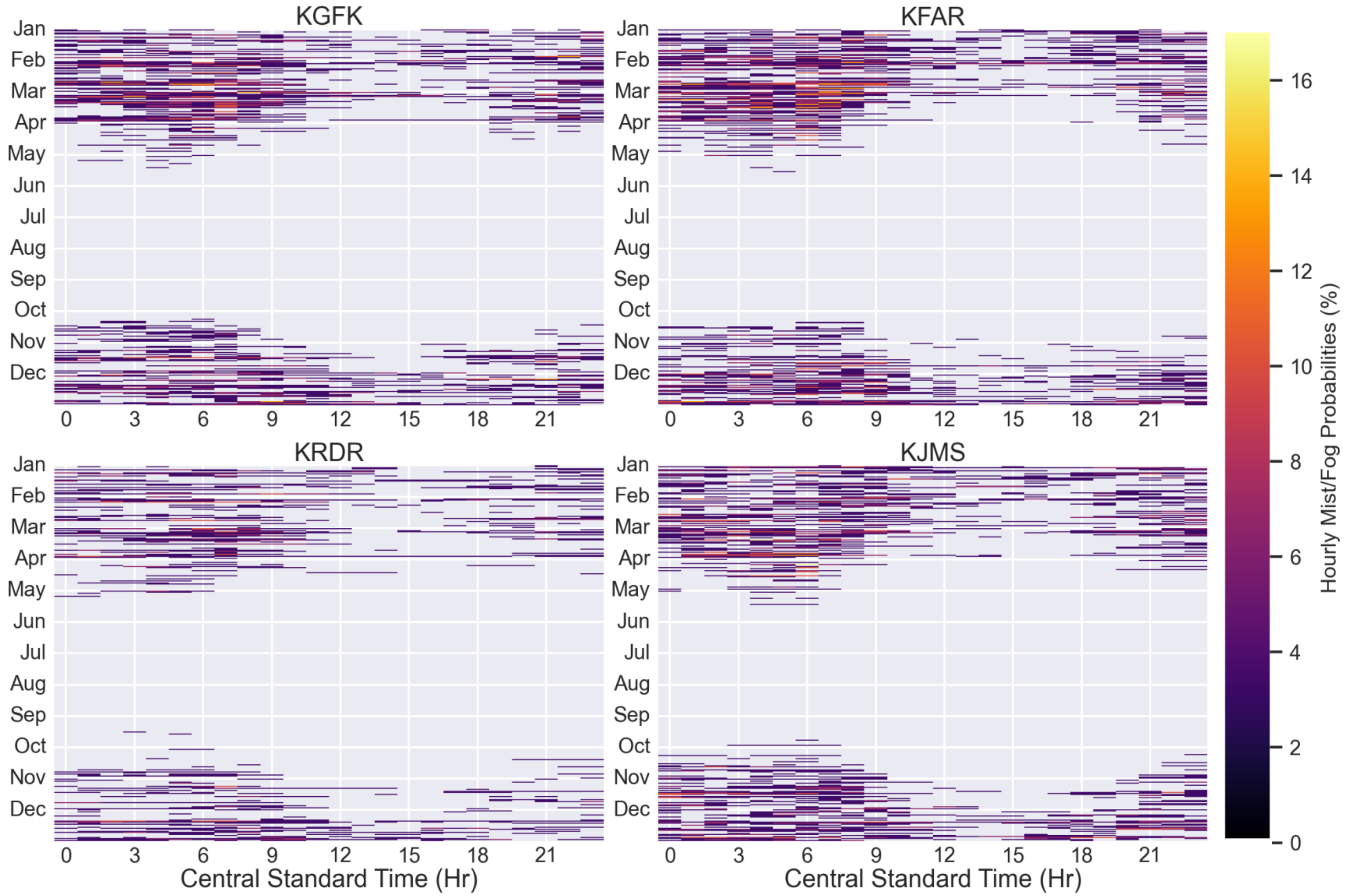
Low Visibility, Low Wind Speed (Mist/Fog) Climatology



Applied Wind Threshold: < 10 m/s

Takeaways: Wind threshold likely filters out blowing snow events; at least two major periods of mist/fog potential.

Low Visibility, Low Wind Speed Supercooled (Mist/Fog) Climatology

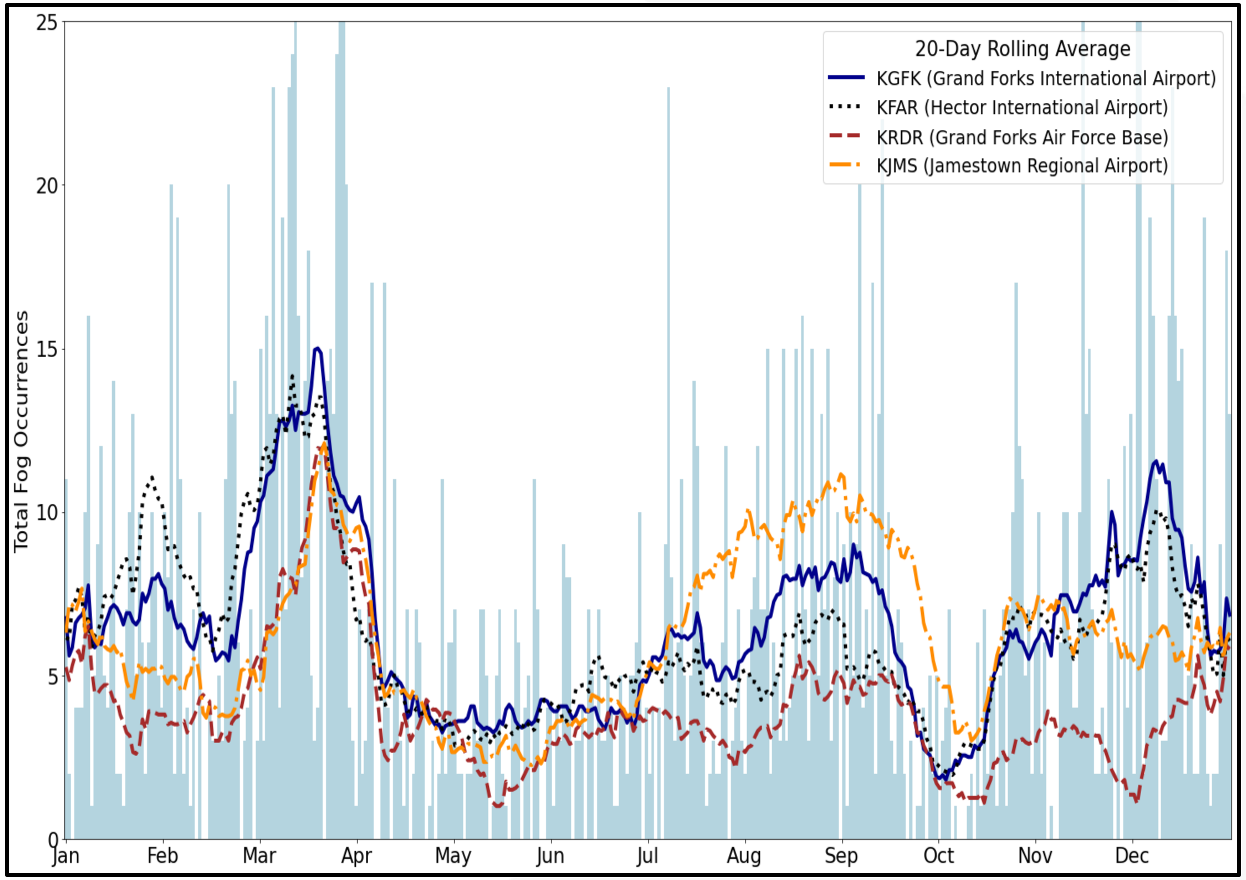


Applied Wind Threshold:
< 10 m/s

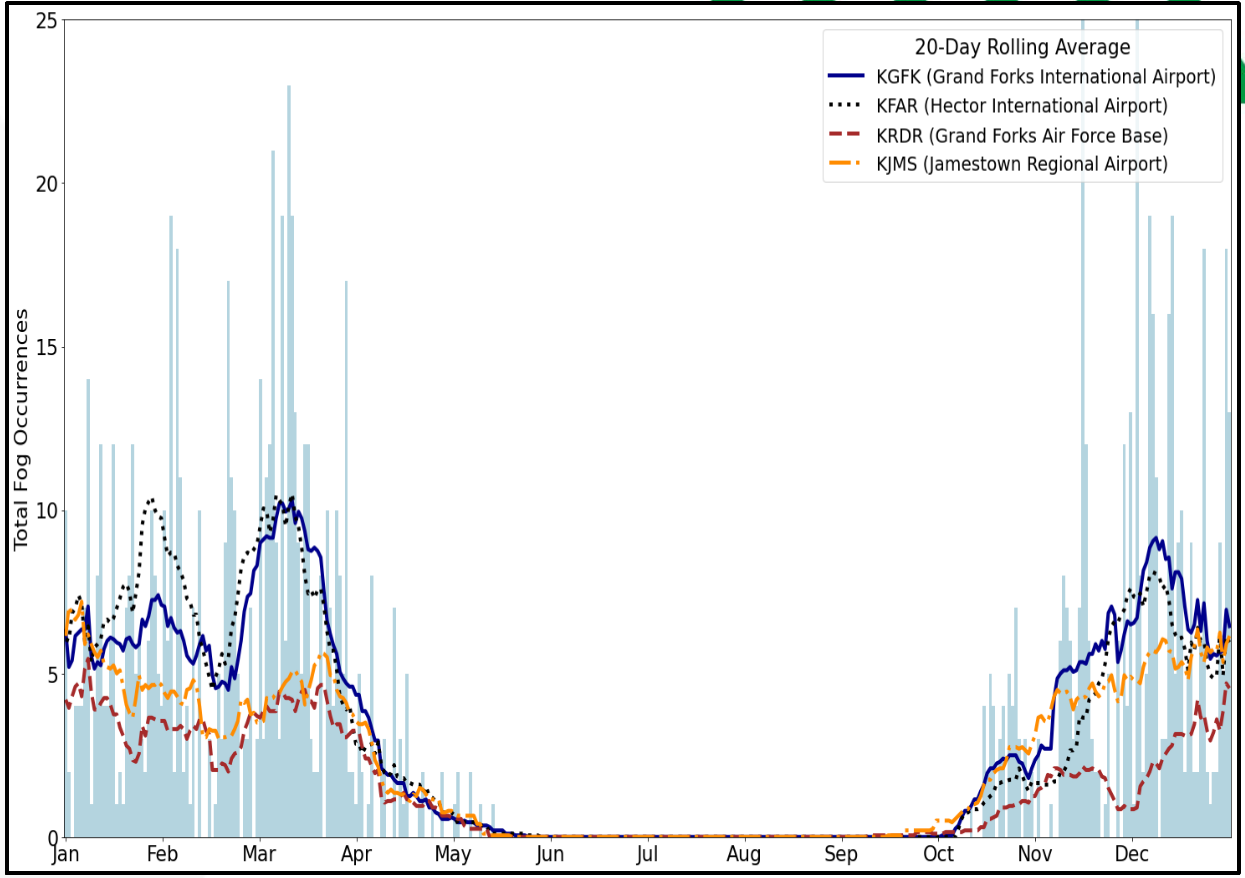
Applied Temperature Threshold:
< 0 °C

Takeaways: Supercooled mist/fog potential exists Nov. through April, maximum during March coincides with seasonal snowmelt.

Fog Climatology: Fog-only Histograms



All Fog

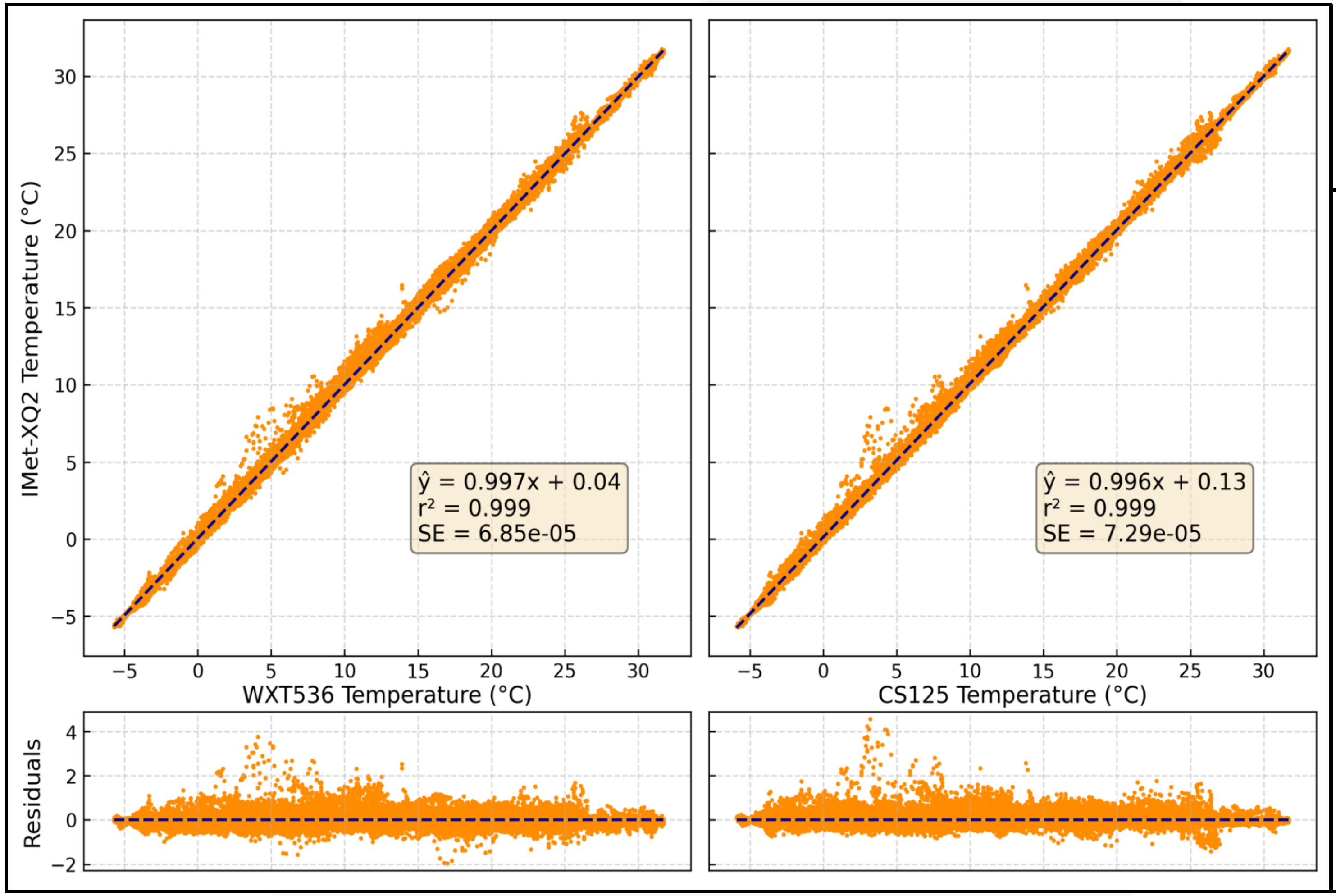


Supercooled Fog

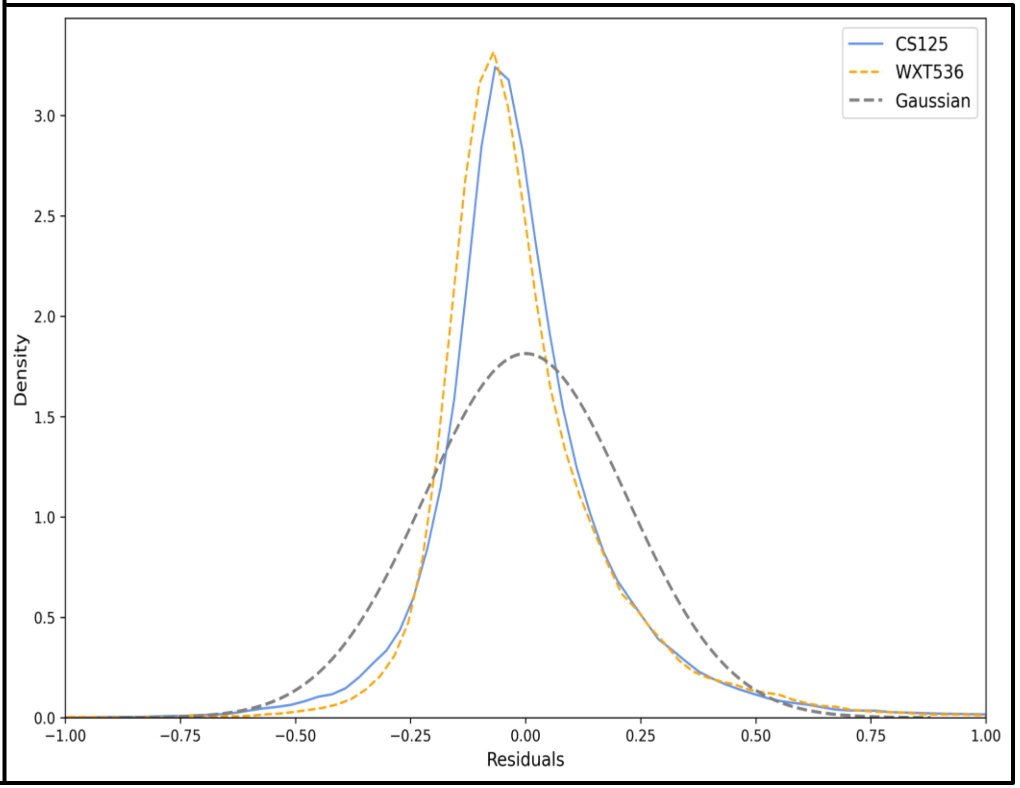
Takeaway: Three periods of increased fog occurrences.

Takeaway: Seasonal supercooled potential from November through end of March.

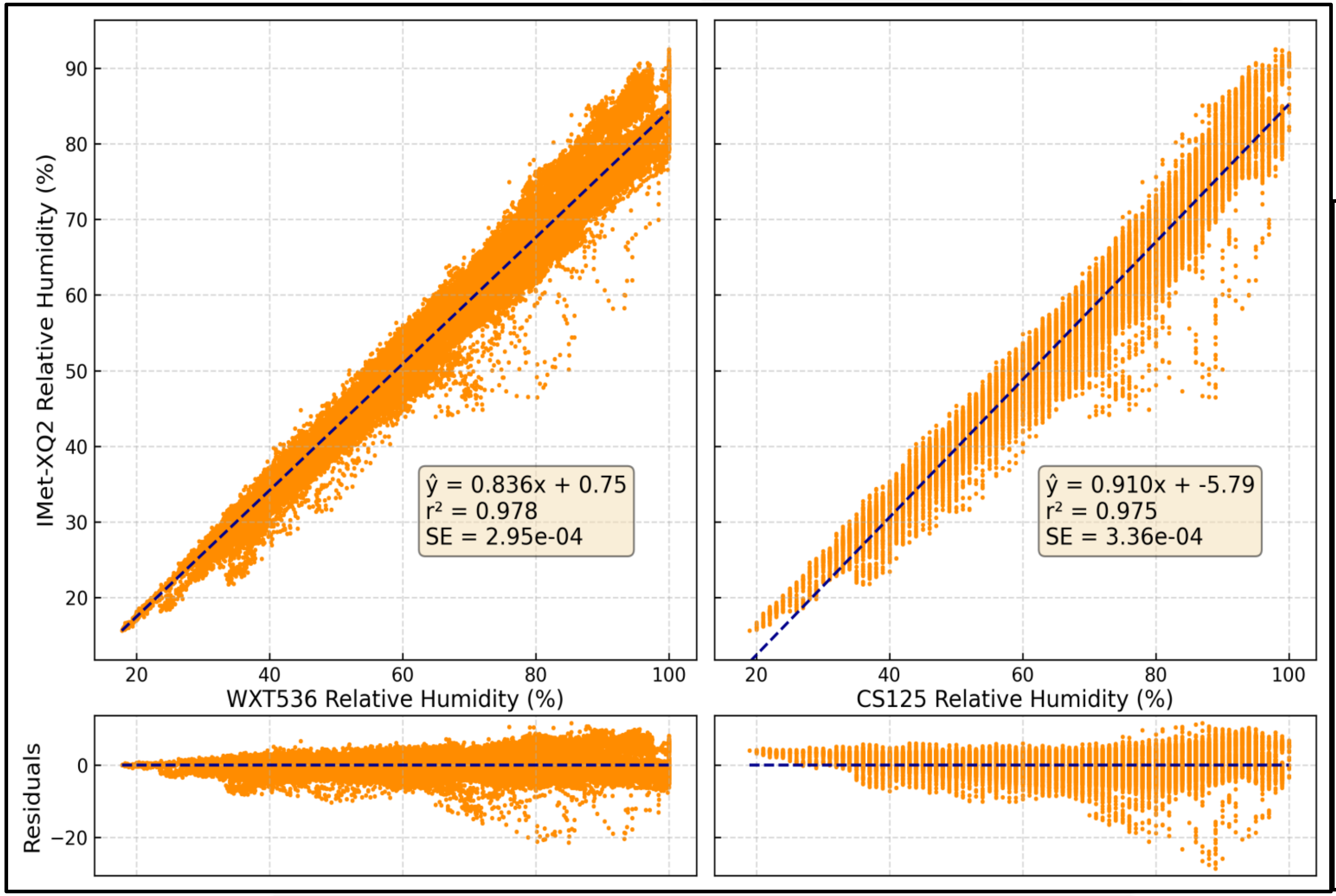
Instrument Analysis: IMet-XQ2 Temperature Sensor



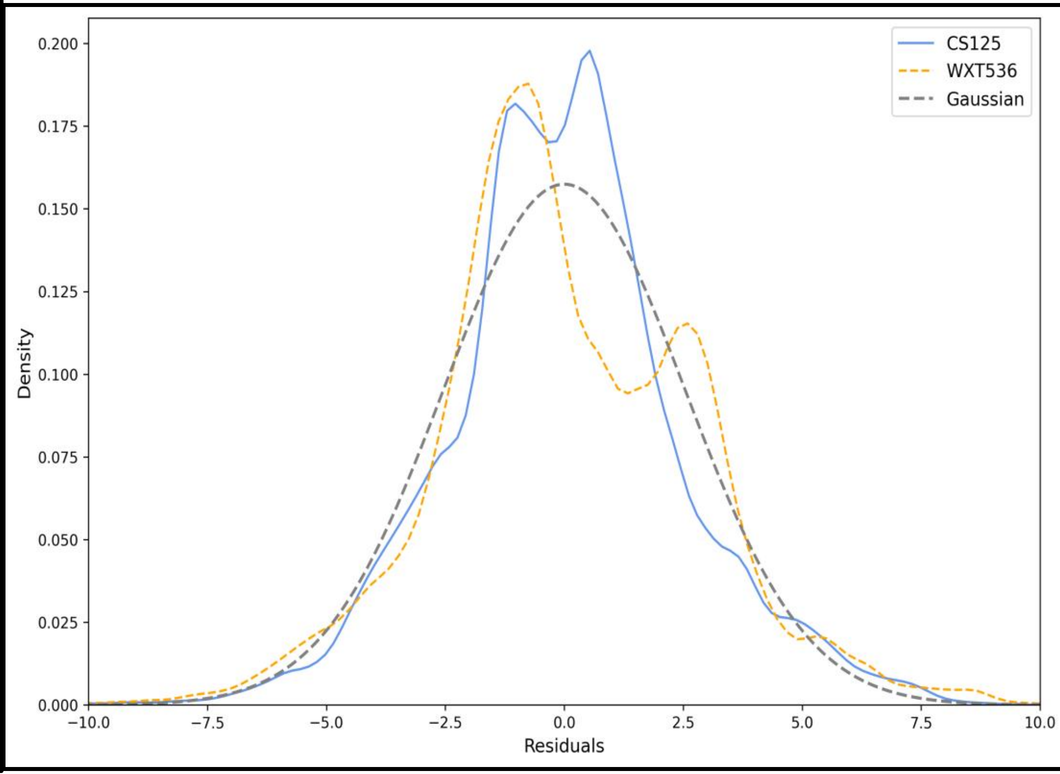
Takeaway: The IMet-XQ2 temperature sensor displays high accuracy and precision.



Instrument Analysis: IMet-XQ2 Temperature Sensor

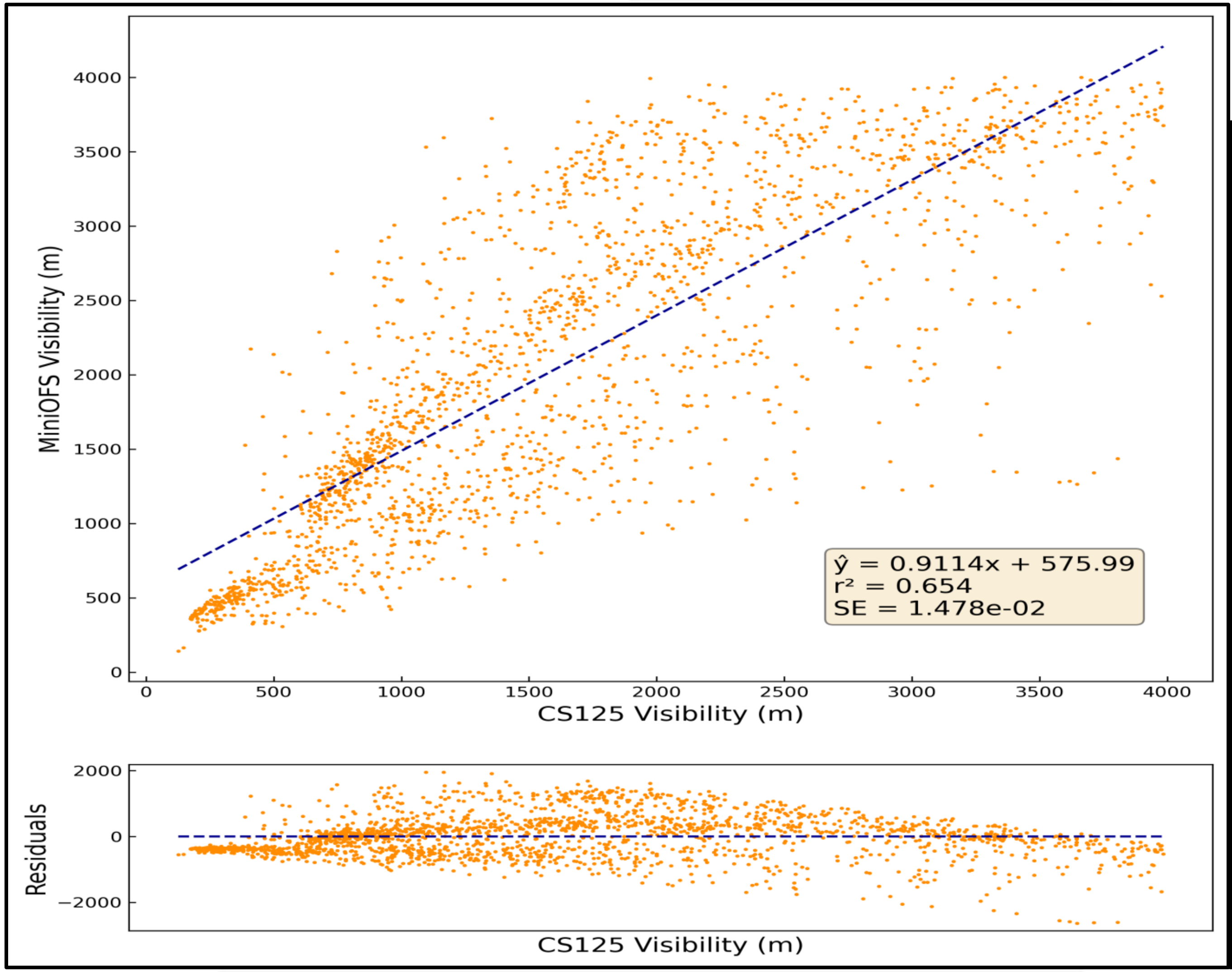


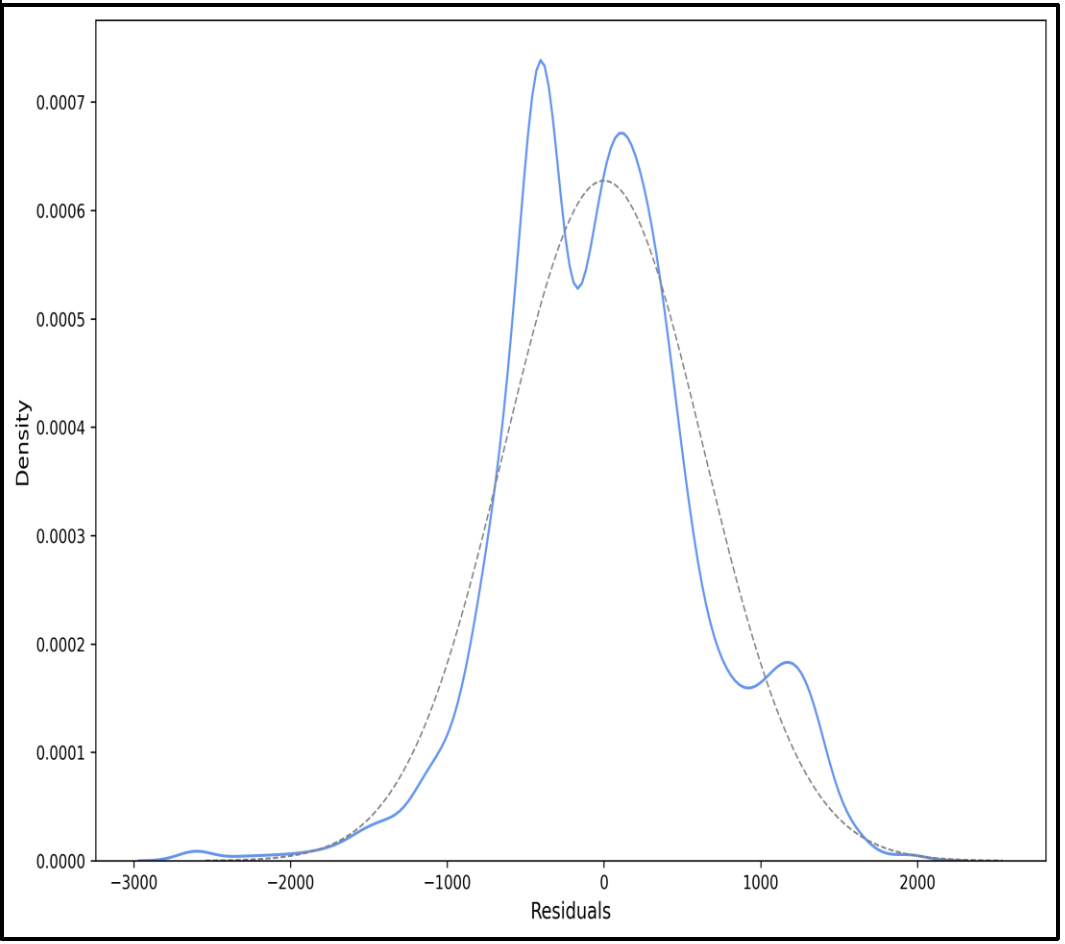
Takeaway: The IMet-XQ2 RH sensor consistently underestimates. Increased variability of measurements.



Instrument Analysis: MiniOFS

Takeaways: Poor correlation and nonlinear relationship between MiniOFS and CS125. There is considerable MiniOFS overestimation.

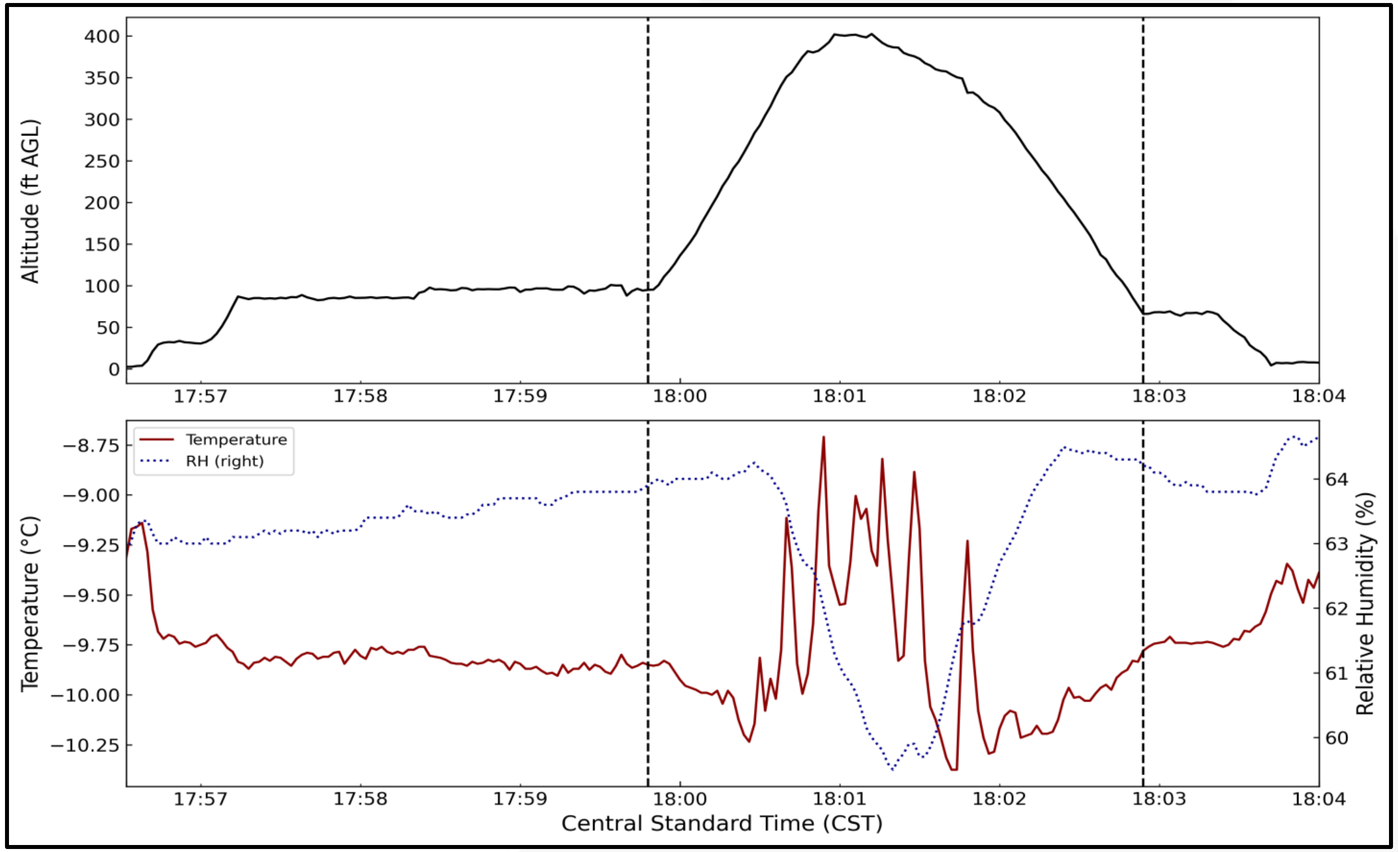


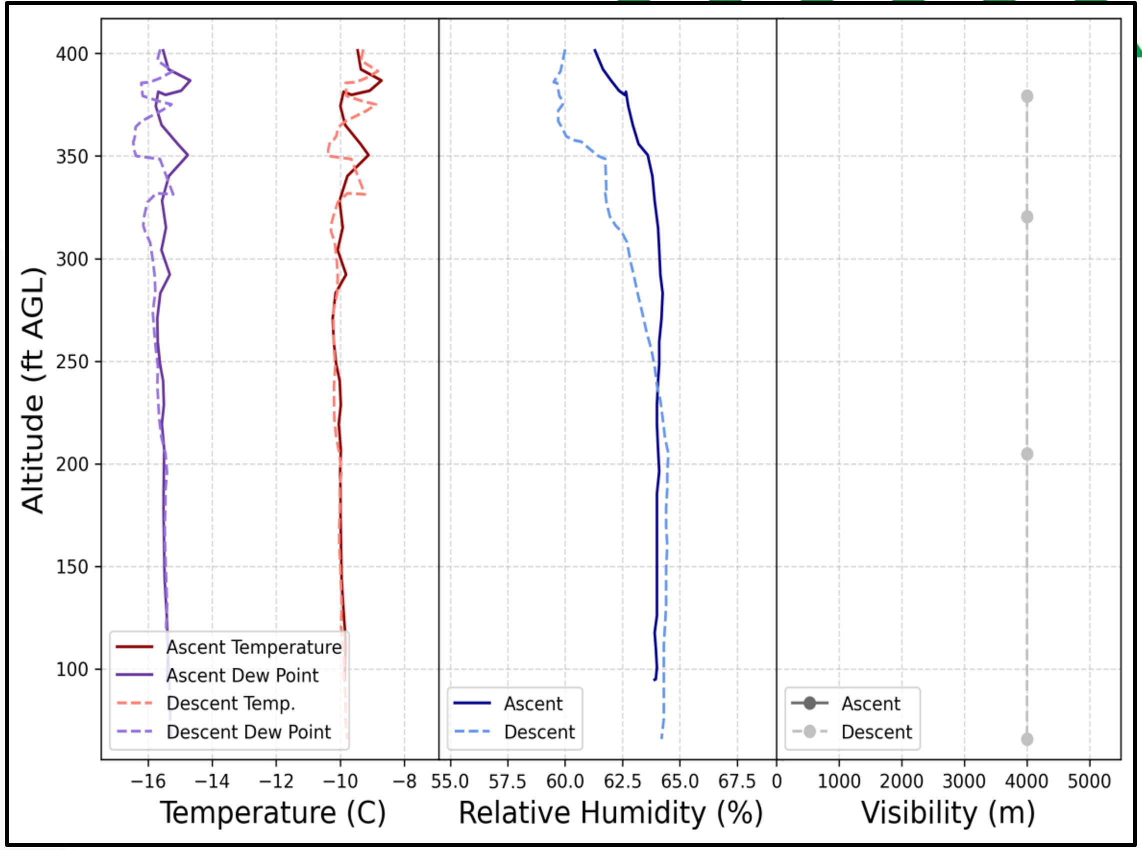


UAS Mission Summary

Date	Visibility Conditions	Vertical Profiles	Surface Wind Speed	Ascent Start	Ascent End	Descent Start	Descent End	Instrument Status
3/7/2023	No Fog	1	~ 5.0 m/s	17:59:48	18:00:58	18:01:12	18:02:54	Both
3/13/2023	No Fog	2	~ 1.0 m/s	15:14:26	15:18:03	15:18:21	15:22:42	Both
				15:22:50	15:26:36	15:27:00	15:32:07	
3/15/2023	Elevated Fog	4	< 0.5 m/s	08:07:28	08:10:12	08:10:27	08:15:15	MiniOFS only
				08:16:29	08:18:16	08:18:39	08:23:46	
				08:46:32	08:49:28	08:50:35	08:53:43	
				08:53:49	08:55:05	08:55:06	08:56:37	
3/23/2023	Elevated to Surface Fog	4	~ 0.5 m/s	08:19:56	08:22:48	08:23:10	08:26:17	MiniOFS only
				08:30:22	08:33:52	08:34:52	08:37:28	
				08:45:30	08:46:52	08:48:39	08:49:54	
				09:16:21	09:21:05	09:22:28	09:27:20	
3/24/2023	Elevated Fog	3	< 0.5 m/s	08:02:26	08:05:32	08:06:38	08:09:27	Both
				08:14:08	08:22:47	08:23:54	08:25:30	
				08:39:42	08:42:48	08:44:01	08:47:31	

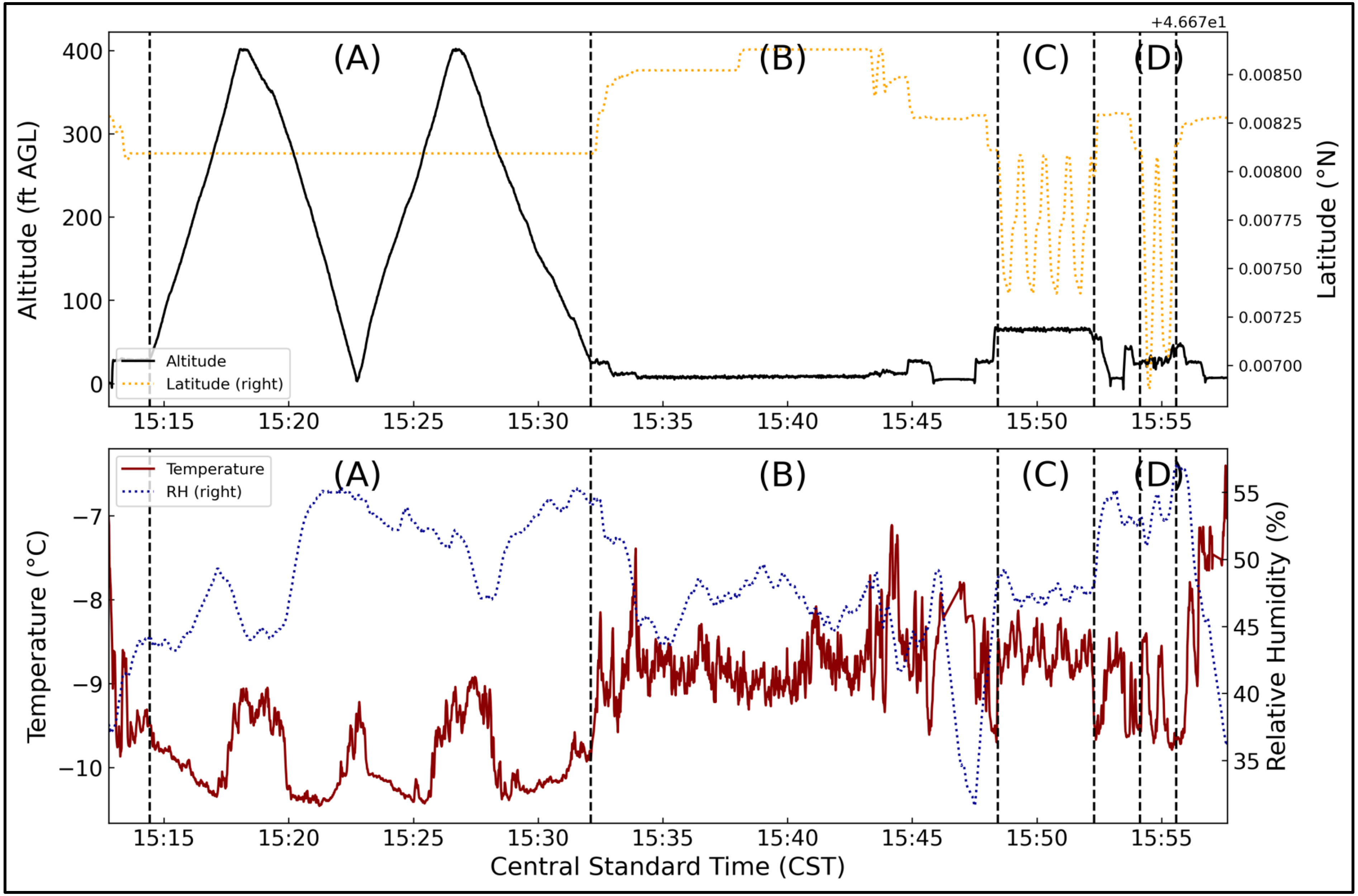
March 7th, 2023: Clear-Air Mission





Takeaways: Ascent/Descent pattern showed sensor response time shifts, particularly for the relative humidity sensor. Good correlation between the ascent and descent.

March 13th, 2023: Clear-Air Mission



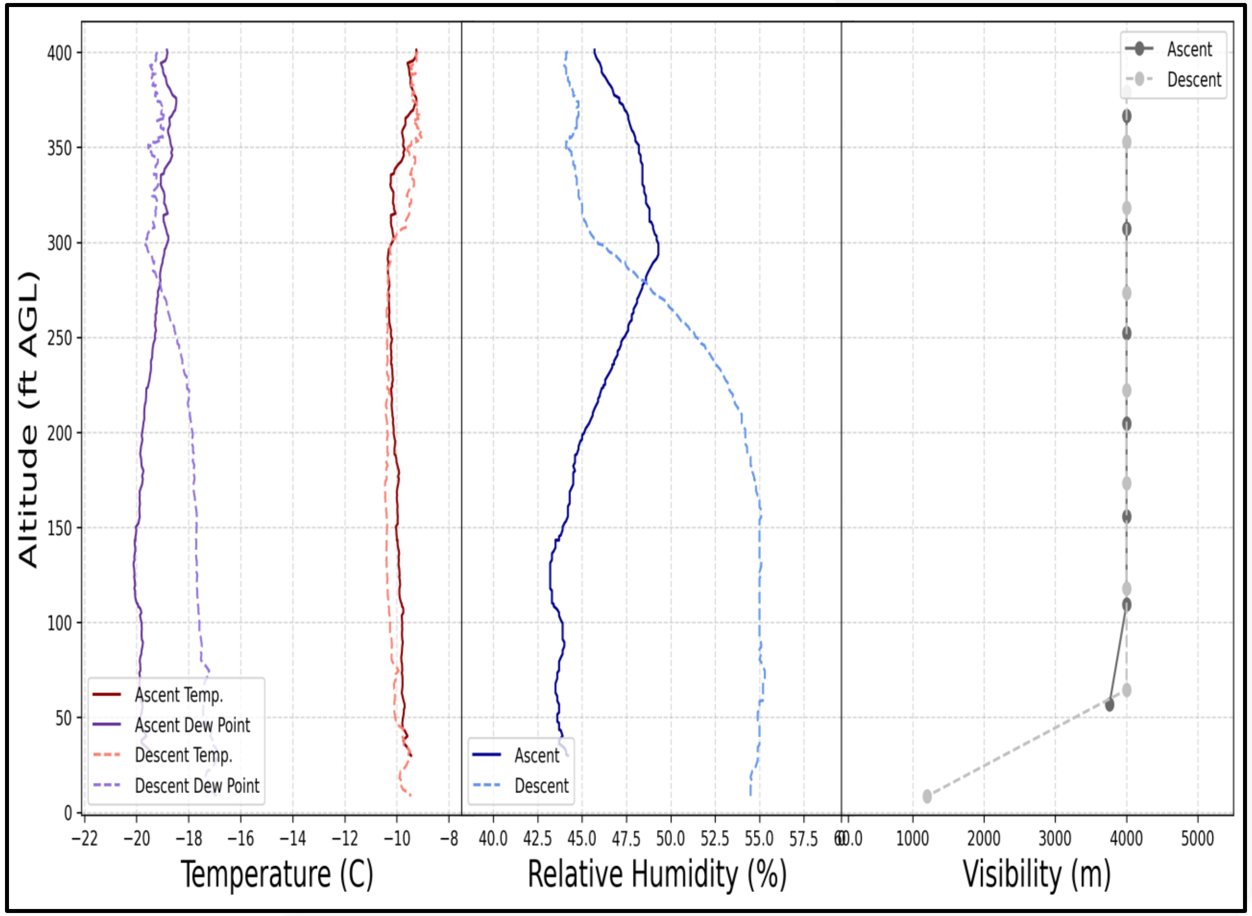
- **A**: Profiling Maneuvers (2)
- **B**: Hovering Period
- **C**: First Racetrack Maneuver
- **D**: Second Racetrack Maneuver

Takeaways:

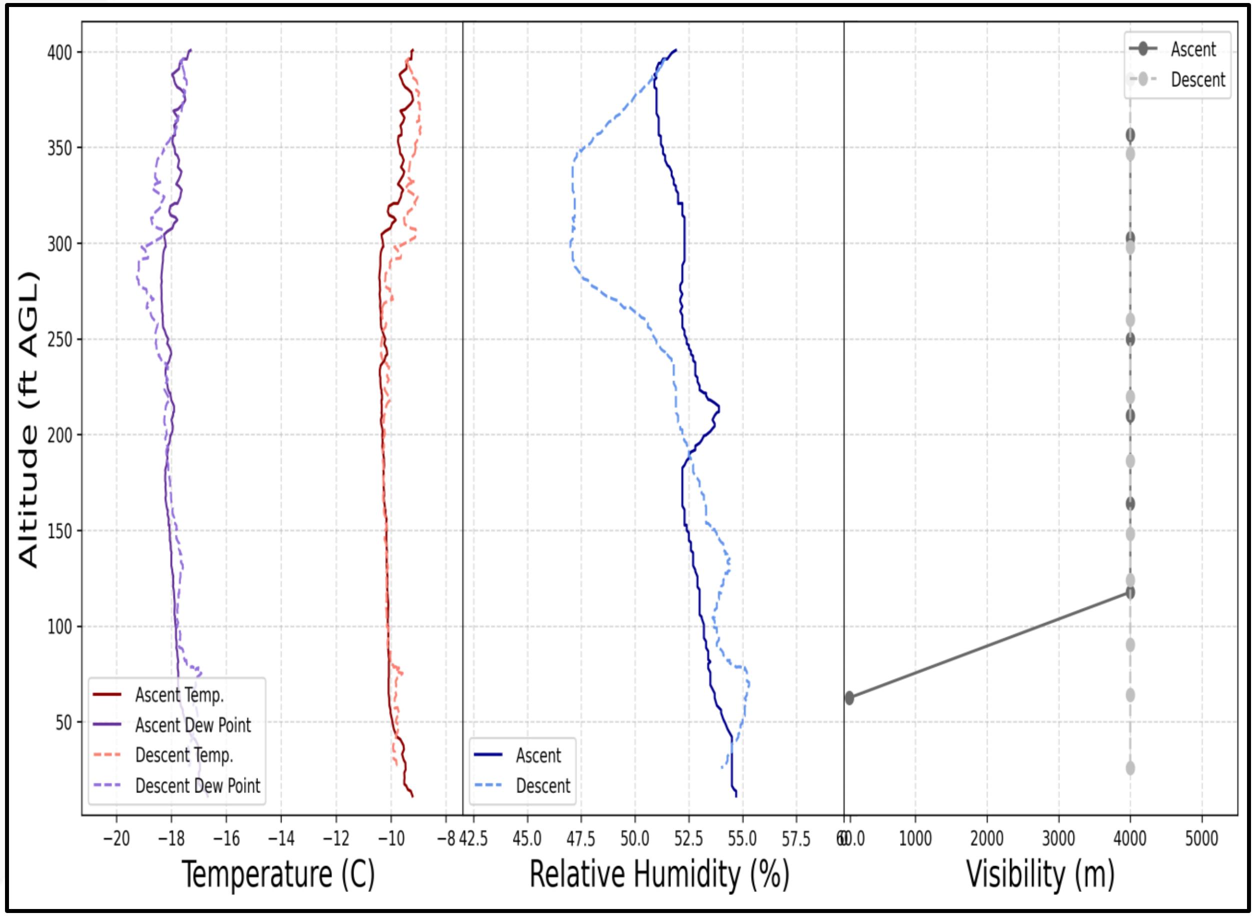
- Substantial discrepancies in the ascent and descents for the RH sensor.
- Continued sensor response time offsets noticeable with temperature sensor.

March 13th, 2023 Vertical Profiles

1st Profile in A



2nd Profile in A

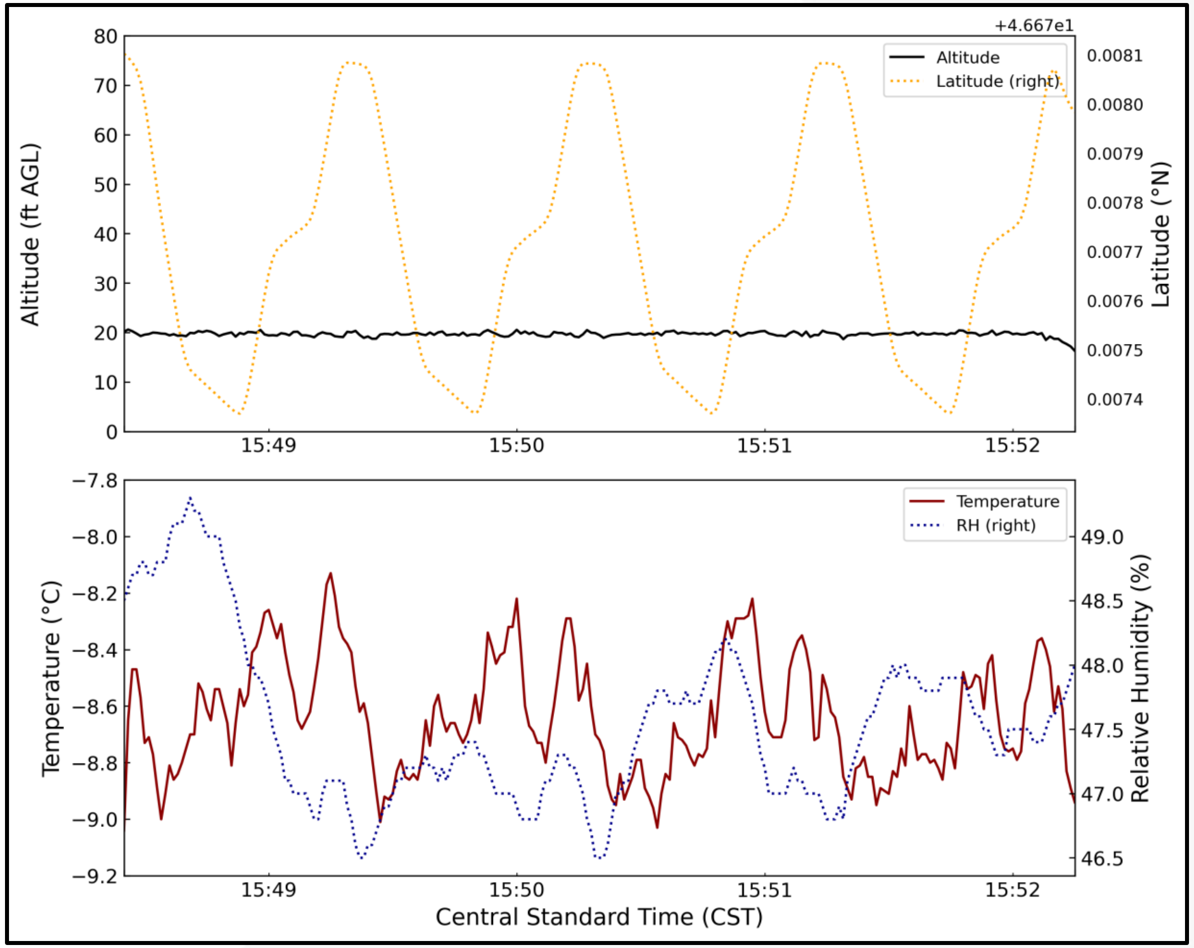


Takeaways:

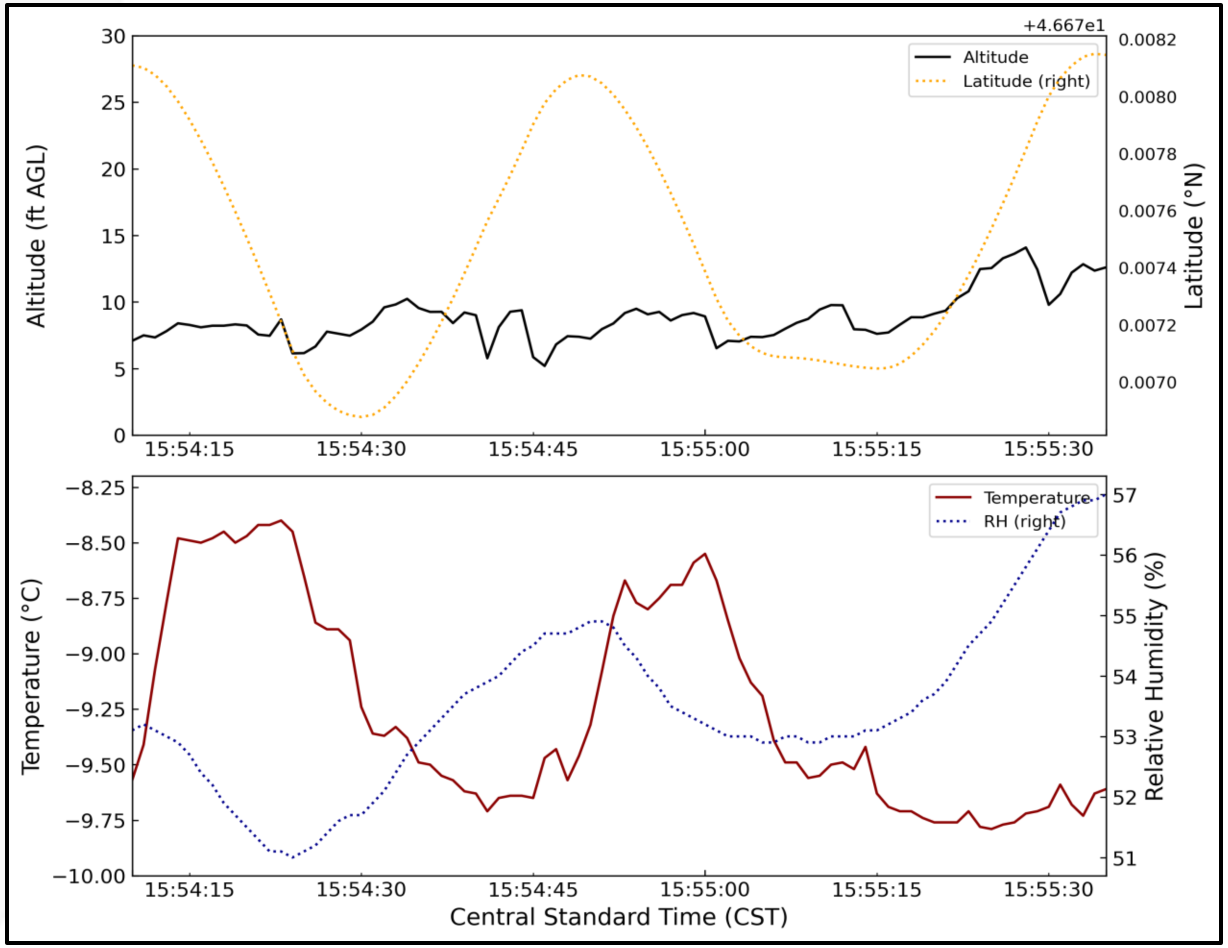
- Cyclical response in the IMet-XQ2 temperature sensor indicates speed/direction bias with UAV movement
- Similar, more subtle response with relative humidity sensor

March 13th, 2023 Racetrack Maneuvers

Racetrack Maneuver in C



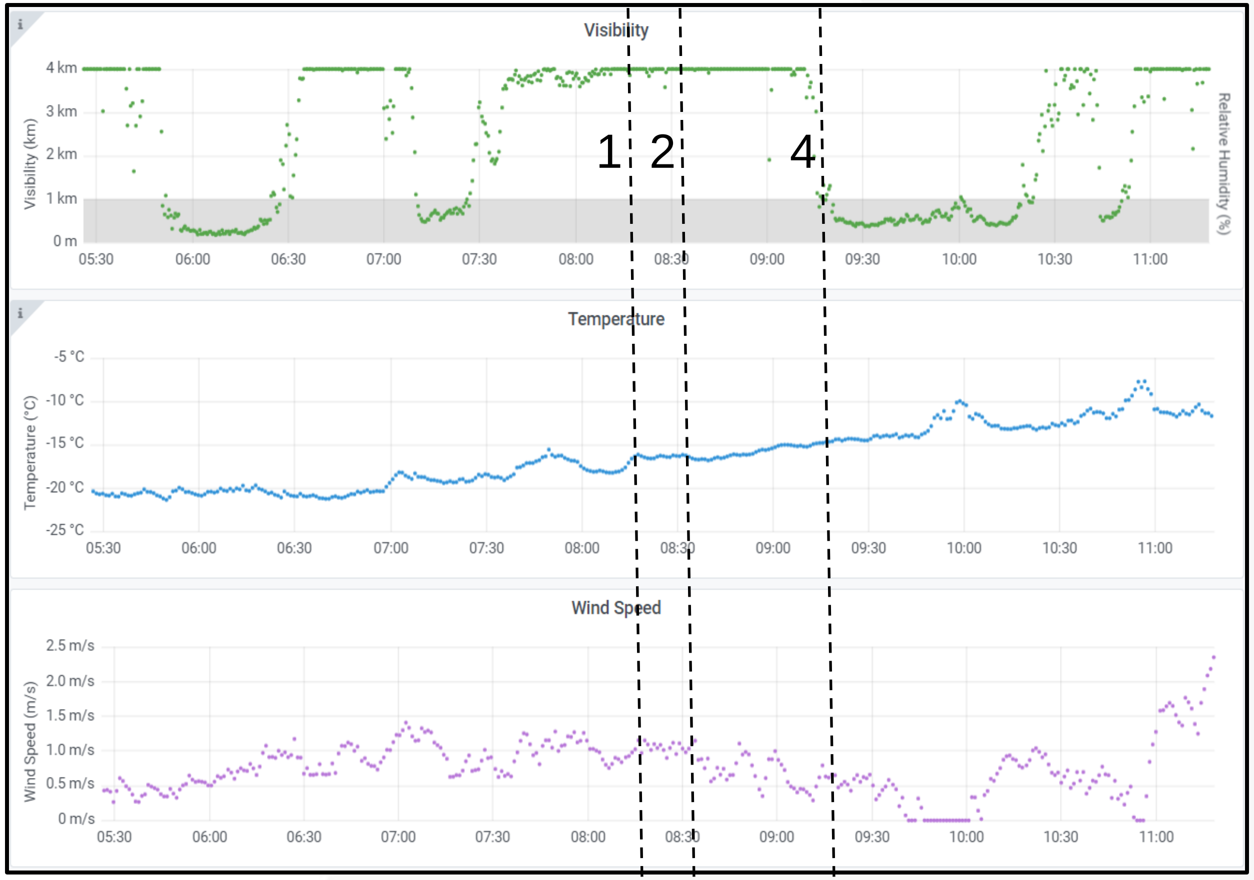
Racetrack Maneuver in D



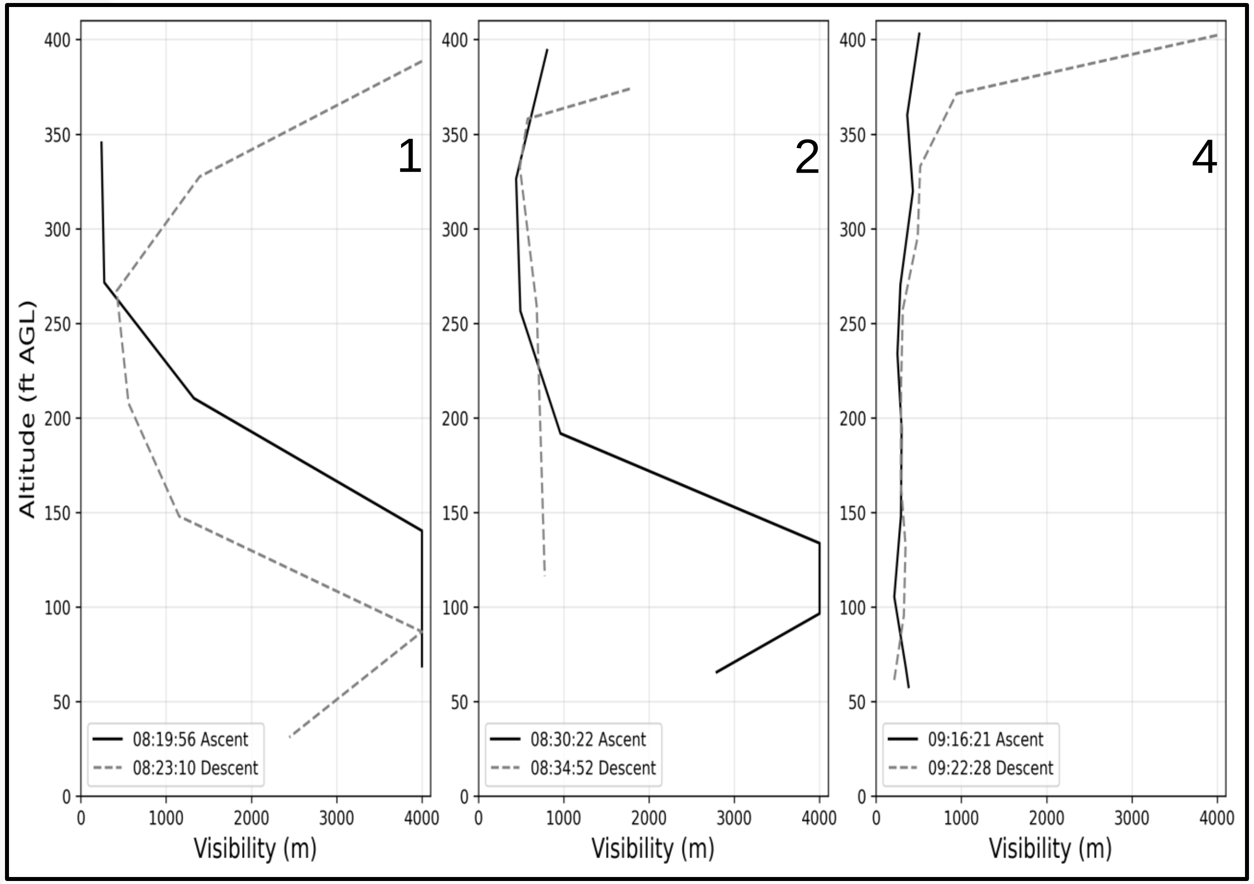
Takeaways:
- Observed strengthening of fog layer coincided with drops in visibilities during profiling missions.
- Top of fog layer 350+ AGL
- IMet-XQ2 sensor malfunctioned early in mission.

March 23rd, 2023 Fog Mission

Tripod surface measurements



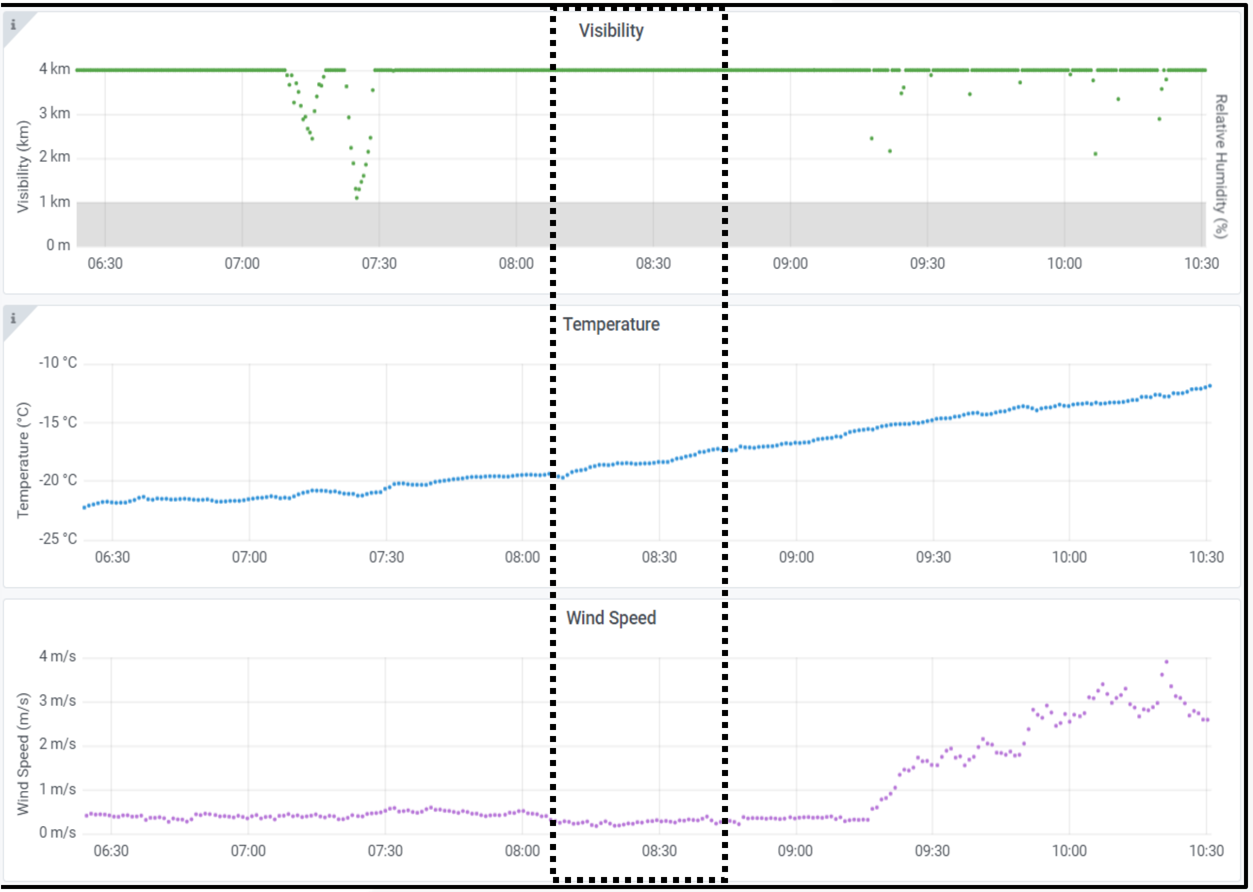
1st, 2nd, and 4th vertical profiling maneuvers

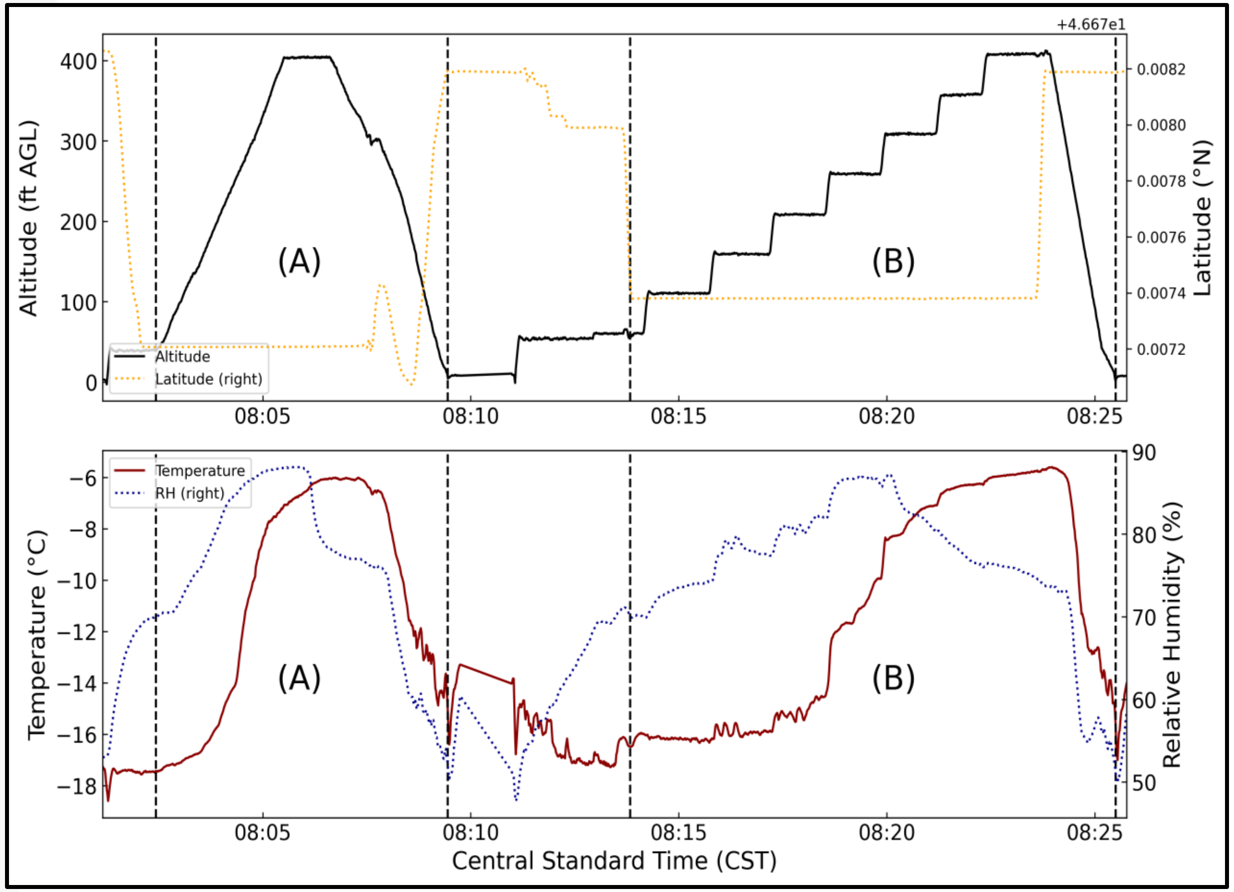


March 24th, 2023: Fog Mission

Takeaway:
- Fog/cloud layer not captured within surface observations.

Takeaway:
- Ascent during vertical profiling maneuver in B used hovering periods to sample specific altitudes

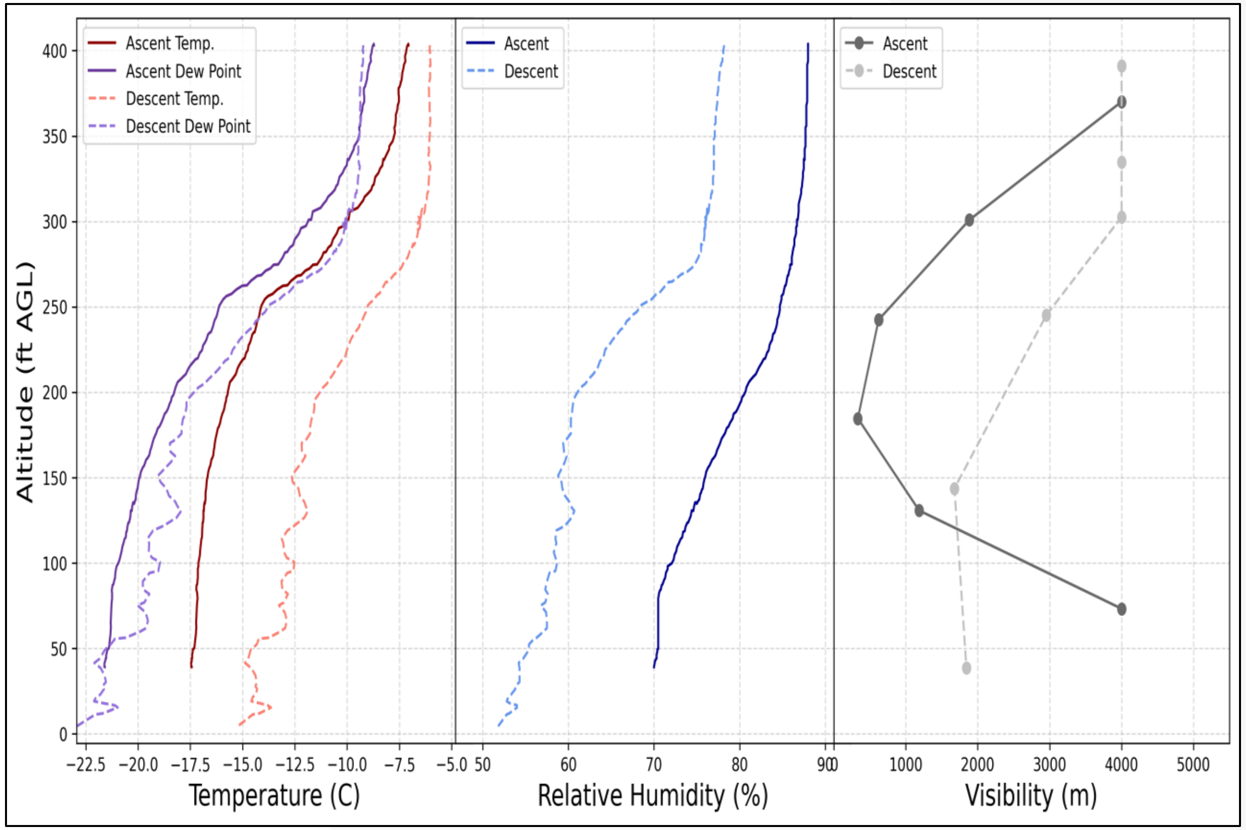




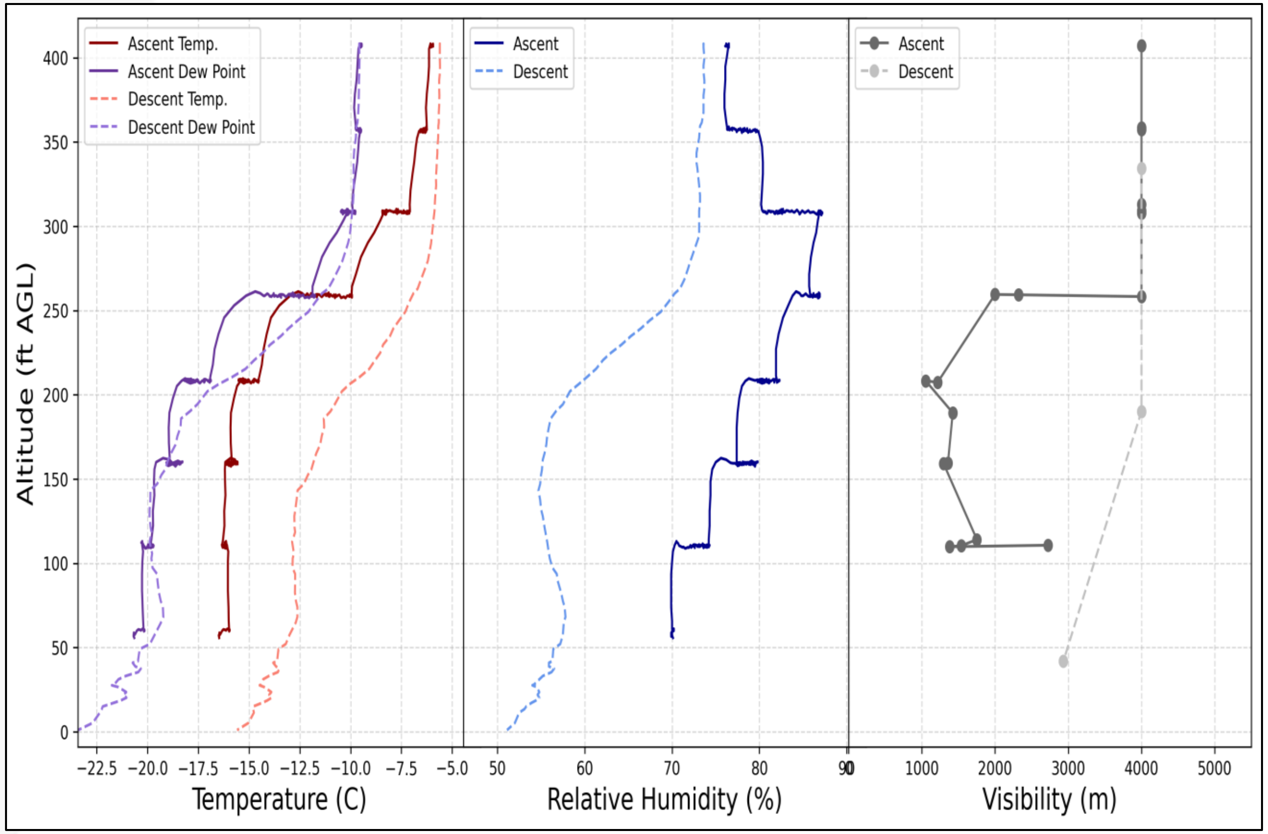
Takeaways:
- Elevated nature of cloud layer not captured on ground-based station.
- Cloud layer depth 100 – 250 ft AGL.
- Inversion observed at top of fog layer.

March 24th, 2023 Vertical Profiles

Profile in A



Profile in B



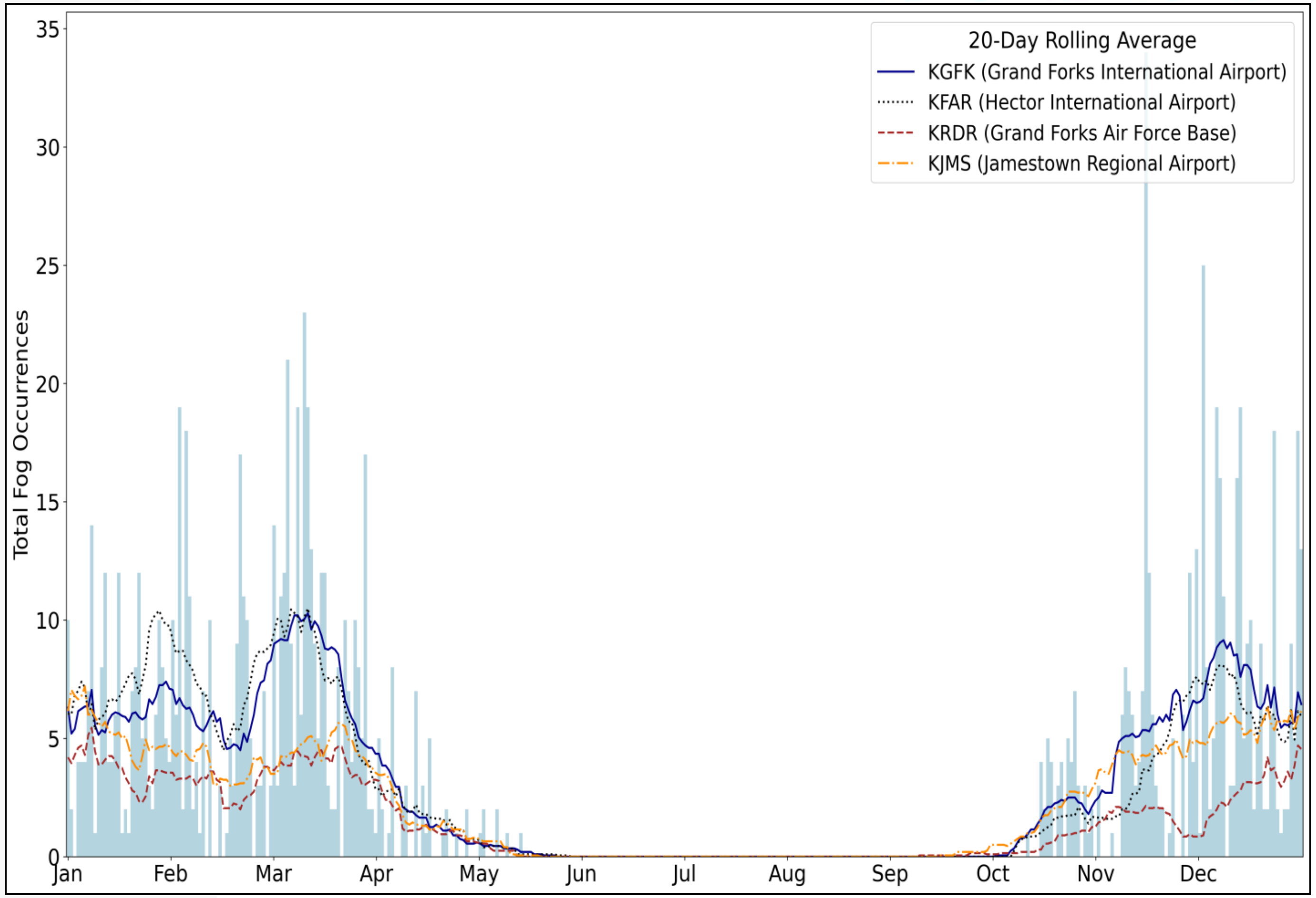
Summary and Conclusions

Fog Climatology

- No substantial increase in fog potential in the Red River Valley.

- Seasonal peaks for fog potential occur:
  - March (cold fogs)
  - August - September (warm fogs)
  - Late November – December (cold fogs)

- Supercooled fog potential occurs from November – April, peaking in March.



Instrument Performance

IMet-XQ2:

- Temperature sensor accurate within 0.5 °C.
- Relative humidity sensor accurate within 10 %; underestimated high relative humidities.
- Sensor response times issues with ascents/descents, particularly with relative humidity sensor.
- Proper housing and protection is necessary to avoid moisture contamination.

MiniOFS:

- Poor correlation with CS125 visibility sensor; accurate within 2000 m.
- Higher precision at lower visibilities; overestimation at visibilities < 1 km.
- The sensor requires hovering or slow maneuvers for representative profilings.

One of the first instances of UAS platform implementation of visibility sensors within fog!

UAS Platform Missions

The UAS platform performed remarkably well during low visibility and supercooled conditions.

<u>Vertical Profiling Maneuvers</u>:

- High resolution profiling of boundary layer.
- Successful identification of the top of multiple fog layers (constrained by 400 ft AGL limit).
- Discrepancies in temperature/relative humidity profiles are related to sensor aspiration, sensor response times, heat contamination issues.
- While significant ice buildup occurred, no noticeable performance degradation was observed

<u>Racetrack Maneuvers</u>: Response of temperature sensor reveals UAV speed/direction bias.

Feasability of the Red River Valley

- A potential operational period of supercooled fog occurs from November through the beginning of April; peaking in March.
- Successful targeting of supercooled fog required appropriate forecasting days prior to the onset of event.
- UAS platform sufficient in determination of top of fog layer for efficient abatement methods.
- The bigger question: **Does supercooled fog occur often enough?**

KGFK	"FG" and/or "BR"		"FG" only	
	All (hours/year)	≤ 0 °C (hours/year)	All (hours/year)	≤ 0 °C (hours/year)
≤ 10 m/s	129	61	80	37
≤ 7.5 m/s	88	41	54	24
≤ 5.0 m/s	53	24	32	14

Average hourly occurrences per year during the 1989-2019 climatology.

Future Work

This project demonstrated the successful implementation of the UAS platform to acquire in-situ microphysical data and an initial determination on the feasibility of a supercooled fog modification project in the Red River Valley.

This is just the start!

- Continued fog research: Cancellation of Red River Valley flights
- More UAS platform missions within fog (fog-prone locations?)
- Internet capability onboard the UAV for real-time data monitoring.
- Better housing setup for IMet-XQ2
- UAS platform FAA approval for:
  - Seeding material integration
  - Nighttime operation
  - > 400 ft AGL operation.
- Additional instrumentation:
  - Newest generation of IMet-XQ instruments
  - Microphysical parameters
  - Low sampling-rate visibility sensors

Acknowledgements

- *Advisor*: Dr. David Delene
- *Committee*: Dr. Aaron Kennedy, Dr. Marwa Majdi
- *Funding Source*: Rapid NSF Fog 2147215 Grant
- *Licensed UAV Operator*: Alex Sailsbury
- Weather Modification International
- Nicholas Camp, Dave Singewald, Jennifer Moore
- Fellow students in the AtSci Department
- Family

Questions?

References

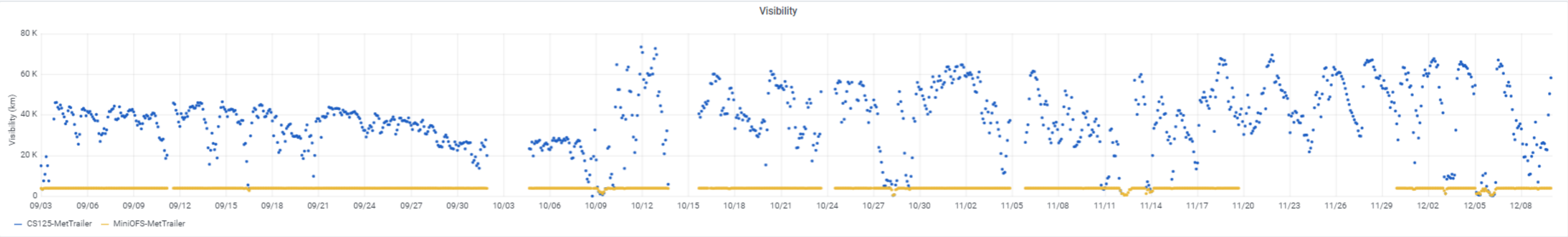
- Brooks, G., 2017: Red River Valley, Manitoba: The Geomorphology of a Low-Relief, Flood-Prone Prairie Landscape. 143–155.
- Capobianco, G., and M. D. Lee, 2001: The Role of Weather in General Aviation Accidents: An Analysis of Causes, Contributing Factors and ISSUES. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.*, **45**, 190–194, https://doi.org/10.1177/154193120104500241.
- Gultepe, I., and Coauthors, 2007: Fog research: A review of past achievements and future perspectives. *Pure Appl. Geophys.*, **164**, 1121–1159.
- ——, A. J. Heymsfield, M. Gallagher, L. Ickes, and D. Baumgardner, 2017: Ice Fog: The Current State of Knowledge and Future Challenges. *Meteorol. Monogr.*, **58**, 4.1-4.24, https://doi.org/10.1175/AMSMONOGRAPHS-D-17-0002.1.
- Islam, A., A. Shankar, A. Houston, and C. Detweiler, 2021: University of Nebraska unmanned aerial system (UAS) profiling during the LAPSE-RATE field campaign. *Earth Syst. Sci. Data*, **13**, 2457–2470, https://doi.org/10.5194/essd-13-2457-2021.
- Kimball, S. K., C. J. Montalvo, and M. S. Mulekar, 2020: Assessing iMET-XQ Performance and Optimal Placement on a Small Off-the-Shelf, Rotary-Wing UAV, as a Function of Atmospheric Conditions. *Atmosphere*, **11**, 660, https://doi.org/10.3390/atmos11060660.
- Liu, X. Y., 2000: Heterogeneous nucleation or homogeneous nucleation? *J. Chem. Phys.*, **112**, 9949–9955, https://doi.org/10.1063/1.481644.
- Michna, P., J. Schenk, R. A. Werner, and W. Eugster, 2013: MiniCASCC — A battery driven fog collector for ecosystem research. *Atmospheric Res.*, **128**, 24–34, https://doi.org/10.1016/j.atmosres.2013.02.009.

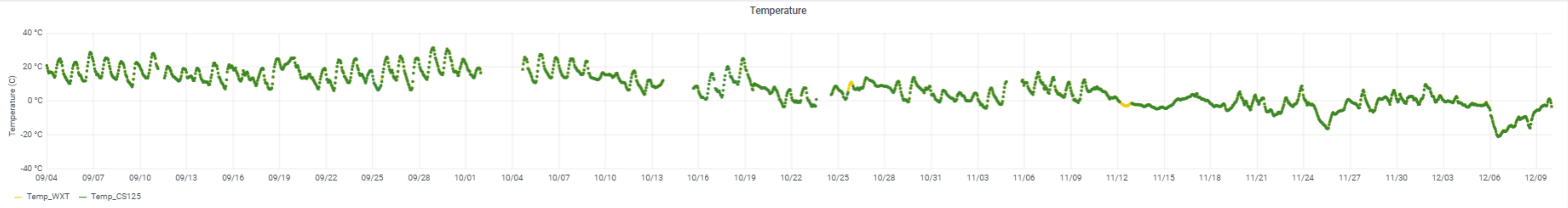
References (Part 2)

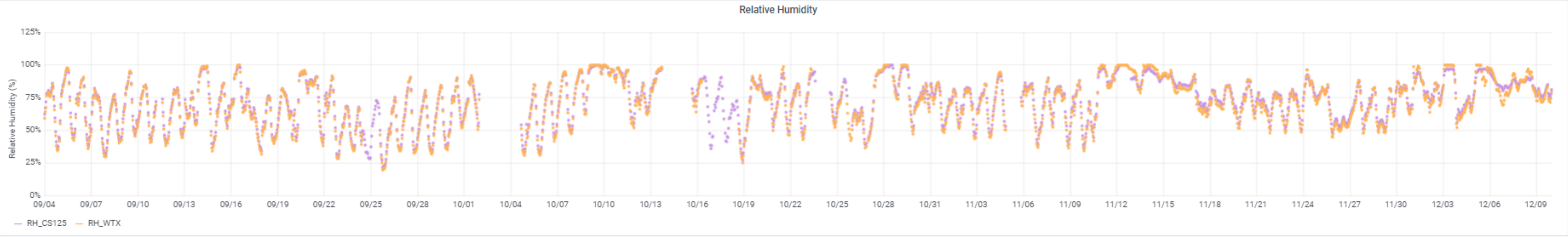
- Oxtoby, D. W., 1992: Homogeneous nucleation: theory and experiment. *J. Phys. Condens. Matter*, **4**, 7627, https://doi.org/10.1088/0953-8984/4/38/001.
- Pruppacher, H. R., and J. D. Klett, 2010: Homogeneous Nucleation. *Microphysics of Clouds and Precipitation*, H.R. Pruppacher and J.D. Klett, Eds., *Atmospheric and Oceanographic Sciences Library*, Springer Netherlands, 191–215.
- Riedl, A., Y. Li, J. Eugster, N. Buchmann, and W. Eugster, 2022: Technical note: High-accuracy weighing micro-lysimeter system for long-term measurements of non-rainfall water inputs to grasslands. *Hydrol. Earth Syst. Sci.*, **26**, 91–116, https://doi.org/10.5194/hess-26-91-2022.
- Vardiman, L., E. D. Figgins, and H. S. Appleman, 1971: Operational Dissipation of Supercooled Fog Using Liquid Propane. *J. Appl. Meteorol. Climatol.*, **10**, 515–525, https://doi.org/10.1175/1520-0450(1971)010<0515:ODOSFU>2.0.CO;2.
- Vonnegut, B., 1948: Variation with temperature of the nucleation rate of supercooled liquid tin and water drops. *J. Colloid Sci.*, **3**, 563–569, https://doi.org/10.1016/S0095-8522(48)90049-X.
- Vonnegut, B., 2004: The Nucleation of Ice Formation by Silver Iodide. *J. Appl. Phys.*, **18**, 593–595, https://doi.org/10.1063/1.1697813.
- Weinstein, A. I., and J. R. Hicks, 1976: Use of Compressed Air for Supercooled Fog Dispersal. *J. Appl. Meteorol.1962-1982*, **15**, 1226–1231.

Instrumentation Analysis

September 1st 2021 to December 9th 2021



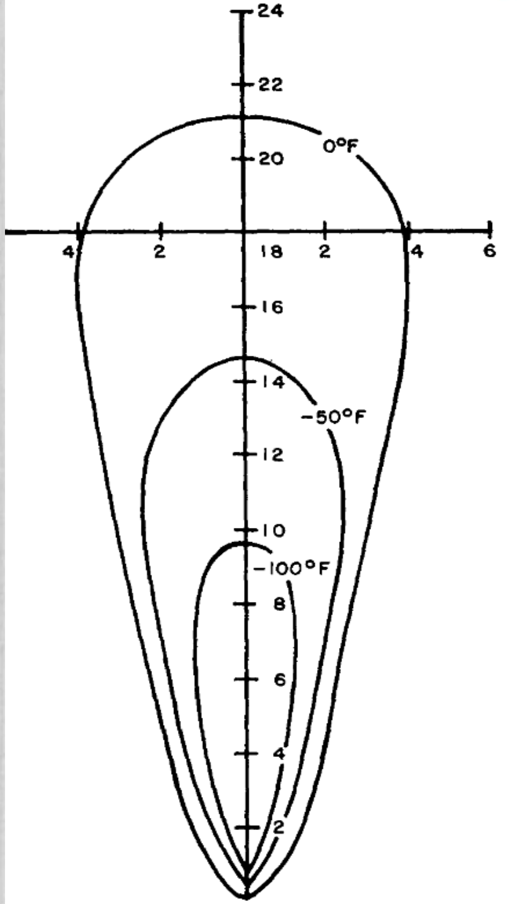




Homogenous Nucleation of Ice

- Occurs ≤ -40 °C. (Pruppacher and Klett 2010)
- Free-energy barrier between phases negligible; formation of lower-energy solid state. (Oxtoby 1992)
- Parcel of air is cooled below threshold.
  - Sublimation (dry ice) (Vardiman et al. 1971)
  - Evaporation (liquid propane) (Weinstein and Hicks 1976)

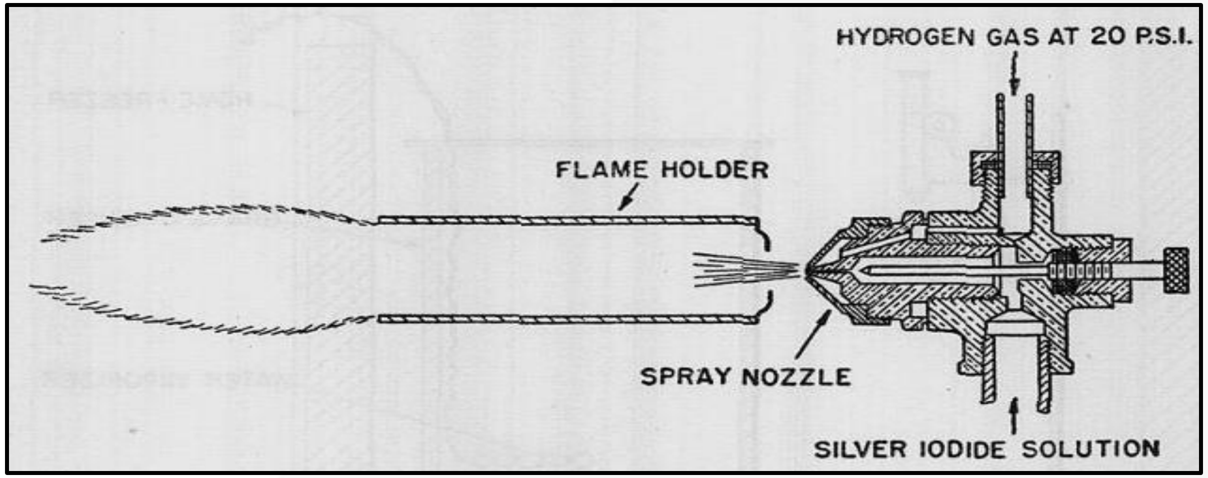
Schaefer 1948. Trail of ice crystals produced in cold chamber by seeding with a needle cooled below -39 °C



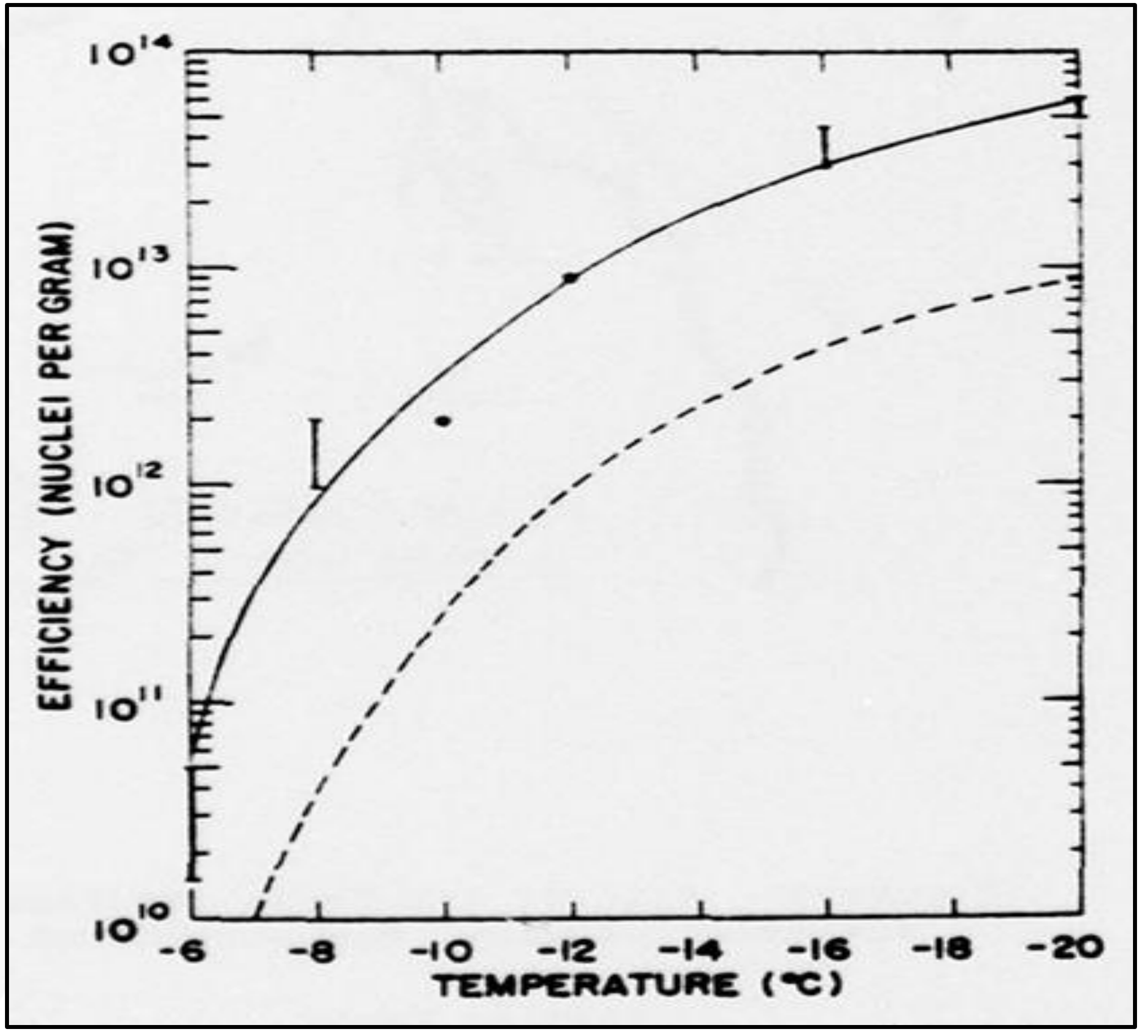
Vardiman et al. 1971. Temperature distribution of expanding propane plume. Scale in inches.

Heterogeneous Nucleation of Ice

- Occurs < 0 °C.
- Materials with good structural match with nucleating phase and strong interaction with metastable phase are suitable candidates. (Liu 2000)
- Silver Iodide (AgI), Lead Iodide (PbI) unit cell dimensions are within 1 % of ice. (Vonnegut 1947)
- Less effective -5 °C to 0 °C (Dyer et al. 1977)



Vonnegut 1948. Schematic of an AgI smoke generator.

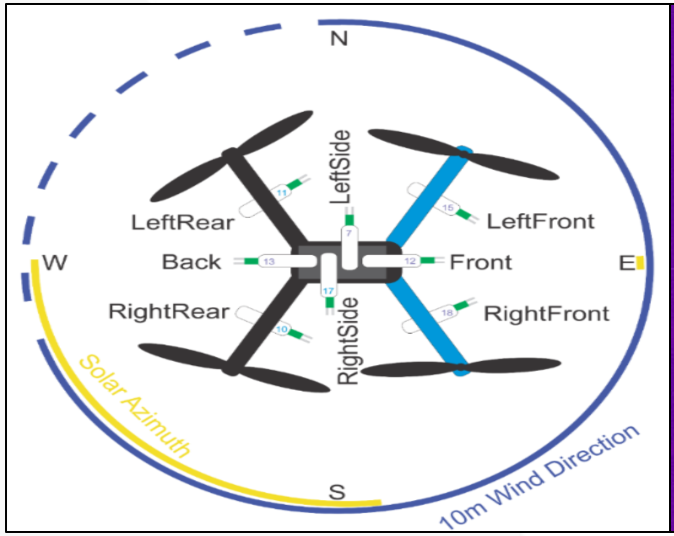


Dyer et al. 1977. Nucleation efficiency of AgI flares. Black line is line of best fit.

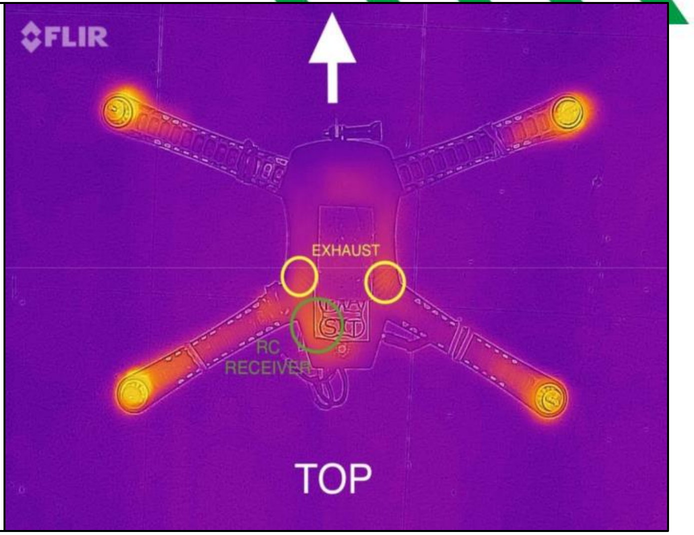
Instrumentation: IMet-XQ2

- Kimball et al. 2020 looked at placements of first generation IMet-XQ on UAV
  - IMet-XQ2 attached to front rotor arms performed best.
  - Underside of UAV deemed practical but with problems.
- Islam et al. (2021) created a novel housing design for the IMet-XQ2
  - Profiling for sensors within housing remained within uncertainties.
  - Sensor response times (particularly for relative humidity) need calibration and correction.

Takeaways: Placement and housing are key, aspiration and sensor response times an issue.



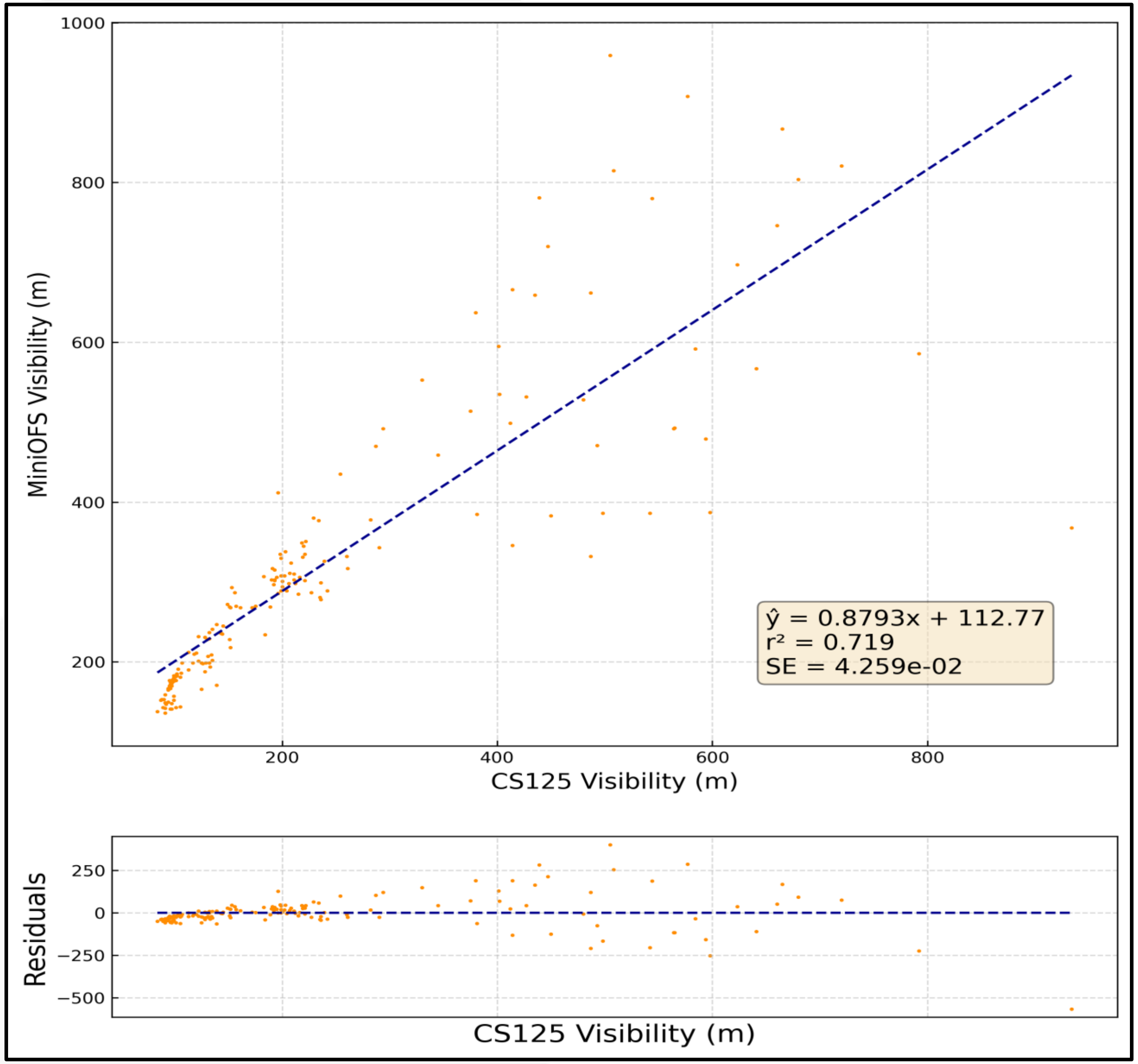
Credit: Kimball et al. 2020



Credit: Kimball et al. 2020

Credit: Islam et al. 2021

March 22nd, 2022 Fog Event



Icy Conditions